**Project Report**
**CESA-2**

# GEA CRDA Range Data Analysis

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28 July 1999

**Lincoln Laboratory**
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*LEXINGTON, MASSACHUSETTS*

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Massachusetts Institute of Technology
Lincoln Laboratory

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*Group 91*

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Lexington Massachusetts

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# EXECUTIVE SUMMARY

Lincoln Laboratory has entered into a Cooperative Research and Development Agreement (CRDA) with four owners/operators of 14 geosynchronous satellites that have potentially close encounters with Telstar 401, which is a drifting geosynchronous satellite in the geopotential well extending from 97-113 degrees West longitude. MIT Lincoln Laboratory's Millstone Hill radar located at Westford, Massachusetts, has been the primary resource for providing data to compute orbits for both the CRDA satellites and for Telstar 401. Orbit accuracy with this tracking data is on the order of 0.5 to 2 km, typically. This report studies the use of CRDA partner range data to enhance the orbit accuracy of their satellites. The results indicate that calibrated CRDA range data from two stations and dense data from Millstone can yield orbits accurate to 100-200 m.

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# ACKNOWLEDGMENTS

We wish to thank Tony Grise of Telesat Canada, Jesus Gutierrez of SatMex, Mark Shannon of PanAmSat, and Peter Staab of G.E. Americom for providing range data for this study. We would also like to thank Karen Fraser for helping to prepare this manuscript.

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# 1. INTRODUCTION

MIT Lincoln Laboratory has entered into a Cooperative Research and Development Agreement (CRDA) with the owners/operators of 14 geosynchronous satellites that have potentially close encounters with Telstar 401, which is a drifting geosynchronous satellite in the geopotential well extending from 97-113 degrees West longitude. The CRDA partners are GE Americom, PanAmSat, SatMex, and Telesat Canada. This effort, in part, involves maintenance of orbits for both the CRDA partner satellites and Telstar 401. The operational aspects of this orbit support are documented in another report [1].

The Millstone Hill radar, operated by Lincoln Laboratory and located at Westford, Massachusetts, has been the primary resource of tracking data for Telstar 401 and the CRDA partner satellites. Millstone is an L-band (1295 MHz) radar with an 84-foot steerable dish. It measures four observables: range, range rate, azimuth, and elevation. The accuracies of these metrics are 5 m or better in range, 5 mm/s or better in range rate, and 5-10 mdeg in the angles. The Millstone radar is well calibrated by ranging to satellites for which very accurate orbits are derived independently using Satellite Laser Ranging data. Orbit accuracy achievable with Millstone alone measurements of geosynchronous satellites varies from 0.5 to 2.0 km. A significant source of measurements also come from the Space Based Visible (SBV) sensor operated by Lincoln Laboratory. SBV is a visible-band, electro-optical camera combined with a 15-cm aperture telescope designed to gather metric and photometric information on a wide variety of resident space objects in support of space surveillance. SBV was launched into orbit in April 1996. It is in a nearly polar orbit with an altitude of 900 km. It measures right ascension and declination with accuracy of 1 mdeg (4 arc seconds). It typically takes tracks of 200 satellites per day operating on an 8 hour per day, 6-day per week schedule. SBV is capable of searching the entire geossynchronous belt within 7 hours.

The purpose of this study is to discuss the use of CRDA partner ranging data with the goal of improving the orbit accuracy of the CRDA partner satellites during encounter periods with Telstar 401 or other drifters. The role of Millstone will also be examined for its ability to calibrate the CRDA range data, and its general use in providing orbit quality. SBV will be used to both enhance and measure orbit accuracy.

The following will first discuss the CRDA range data that has been made available. Procedures have been put in place to automatically receive and convert this data into a Millstone compatible format, and this will be briefly discussed. Following this, the methodology of orbit determination and CRDA range data calibration will be presented. Next, from the various CRDA range data received, a number of exemplary cases will be given, which illustrate the calibration and the effect on the orbit accuracy.

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# 2. PROCEDURES

## 2.1 DATA RECEIVED

The data received from CRDA partners fall into two categories. The first category contains data initially obtained as samples and cover from a few days to over a month. The second category contains data being collected on a regular basis, and are operationally calibrated and available for inclusion in the orbit fits for the CRDA satellites.

All data have been received by e-mail. Data have been received routinely from two CRDA partners, Telesat Canada and SatMex. The range data e-mail from these two CRDA partners automatically initiate scripts, which read the e-mail files and write the range data into a Millstone data format. An error is also assigned to the range measurements as determined from the analysis, which will be discussed in the next section. The two other CRDA partners, PanAmSat and GE Americom, have supplied samples of their range data, which have also been converted into the Millstone format. The GE Americom data have been over just a few days and are not abundant enough for significant analysis. Some examination has been made of this data, but the results will not be discussed here.

## 2.2 COORDINATES

All CRDA partners have supplied coordinates for their stations. The orbit determination program DYNAMO used at Millstone Hill requires input station coordinates to be Cartesian and in an internal Lincoln Laboratory reference frame which is close to WGS84 for the purposes of this work. PanAmSat provided their station coordinates in NAD83, which should coincide with WGS84. Telesat Canada provided one of their stations in WGS72, and this was converted to WGS84. For the other stations, CRDA partners have provided a geodetic latitude, longitude, and height, and the geodetic datum parameters $a_{e\,=}$ semi-major axis of the earth and $1/f$ = flattening coefficient for the earth, which permitted conversion to Cartesian. These datums could not be identified, and it is not certain what the offsets from WGS84 are. Some of the offsets can be partially absorbed by range biases, which are determined during the calibration. The stations will be referred to by the names or locations provided by the CRDA members. No information has been obtained with regards to technology or performance of the CRDA partner tracking stations, and so this will not be discussed in this report.

## 2.3 ORBIT DETERMINATION AND CALIBRATION

The data from the CRDA partners were obtained not calibrated or, in other words, did not have range biases applied. The CRDA partners have their own calibration of the range biases but for this study it was desired to have the calibration determined independently. A range bias between a tracking station and satellite is due to the station hardware, to the satellite transponder, and to unmodeled atmospheric refraction. The CRDA partners have two stations generally, and it is difficult to determine range biases for both station-satellite pairs from just their ranging data alone. The biases can be absorbed in the orbit solution and incorrect values may result. At best, the bias for one station-satellite pair can be determined if the other is fixed at some value. To determine both station-satellite biases, another source of tracking data is necessary to provide an independent source of orbit control. During encounter periods, Millstone is providing significant tracking of CRDA satellites, and this helps provide an orbit which can be used to calibrate the CRDA data. Millstone, itself is well calibrated, as will be discussed below. Otherwise, it is necessary to use whatever available tracking data that are nominally collected for these satellites from the rest of the Space Surveillance Network (SSN) to compute orbits and determine the biases.

The first attempt at looking at this CRDA data calibration was made when there were significant Millstone data available. The CRDA data were unweighted in the orbit fits, i.e., only compared against an orbit based primarily on the Millstone and other SSN data. The results often showed CRDA range residuals with a bias and a daily periodic signature, having a magnitude of a few hundred meters. This large residual error was particularly predominant in the SatMex data. In particular, both SatMex stations, located in Mexico, showed large residuals with a diurnal signature. These residuals seemed to indicate that this CRDA data were mostly reflecting the error in the orbits computed with the Millstone and other SSN data. Therefore, the CRDA data had to be weighted and used in the orbit fit and biases determined in an iterative process. In this process, the CRDA data were given an error from 4-16 m. When the CRDA data were weighted in the orbit fits, the residuals showed mostly just a bias and no longer exhibited the diurnal signature. The CRDA data were now helping to determine the orbit. The calibration was then continued iteratively as a bias was determined and applied, the orbit refit, and a bias refinement established. This bias can then be monitored for change if ongoing data are collected.

As will be discussed further, various length arcs were used in the orbit fits. If possible, two-week arc lengths generally were used for the initial bias determination and orbit quality assessment. Arc lengths of roughly four weeks were also often used to determine the bias. These developed naturally from the fact that Millstone typically tracks a CRDA satellite for four weeks during an encounter support.

To fit through maneuvers, the method is to solve for one or more thrust parameters in the along track (E-W), cross track (N-S or inclination), and radial directions. For the general encounter analysis [1], the strategy is to solve for all three and only require knowledge of the start time of the maneuver. This works well enough for the encounter analysis but it does not work quite as well when trying to calibrate the range data to the noise level of the data. Generally, it is noted that the CRDA range residuals are noisier than normal as a result of the maneuvers. This seems to be because there may be three maneuvers over a few days and solving for all thrust components over this period is difficult. Solving for just the primary thrust component has not worked well and more analysis is required to understand why.

It is hoped that during periods of dense Millstone tracking that the biases of the CRDA range data will be determined within the noise level of the data. At other times, a bias can be maintained at some level by using the other available SSN nominal tracking.

# 3. ANALYSIS RESULTS--ORBIT DETERMINATION AND CALIBRATION

This section presents several examples of CRDA range data calibration and the orbit quality that results when this calibrated range data are added to the Millstone and other available SSN data. Examples have been chosen that illustrate this with and without the use of dense Millstone tracking. In a few cases, results are also presented which show how well just CRDA range data performs in the orbit determination software, DYNAMO, used for this study. In these cases, the CRDA data will be considered to be uncalibrated, i.e., no effort was made to calibrate the data; and also to be calibrated, i.e., some adopted set of range biases applied. When using CRDA data only, the orbit determination often had difficulty solving for all the thrusts so known values had to be used.

## 3.1 EXAMPLE 1: TELESAT CANADA, ANIK E1, DECEMBER 1997-JANUARY 1998

This data set consisted of a little over a month of Telesat range data for Anik E1 plus dense Millstone tracking since this was a Telstar 401 encounter period. There were also other SSN data as well as data from the SBV (Space Based Visible) sensor operated as a contributing sensor to the SSN by MIT Lincoln Laboratory.

The data of interest were over the period of Days 343 of 1997 to Day 011 of 1998. The Telesat data were from two stations called Allan Park and Edmonton both located in Canada. Allan Park is near Toronto and is relatively close to Millstone located in Massachusetts. Edmonton is in Western Canada. The data were distributed continually over the 34-day period, and typically a measurement was made roughly every three to four hours. There were six maneuvers over this period, either east-west or north-south adjustments, as well as momentum adjustments. There were typically two tracks of Millstone data of range, range rate, azimuth, and elevation measurements every day. A Millstone track typically consists of 5-15 sets of measurements. SBV tracked roughly once per day and provided measurements of right ascension and declination with each track.

The goals of this example were:

- To determine the calibration of the Telesat Anik E1 data in terms of range biases in order to yield more accurate range data.

- To determine the degree of orbit accuracy enhancement that the calibrated Telesat range data could provide when added to the Millstone and other SSN data.

The means of calibrating the Telesat range data involved an iterative procedure, as discussed. The Telesat range data were first given a nominal error of 8 m and folded into an orbit determination with the Millstone data. In this case, two 18-day orbit fits were actually performed, one over Days 343-360 of 1997 (modeling through five maneuvers) and the other from Day 359 of 1997 to Day 011 of 1998 (modeling through one maneuver). A longer arc over the entire period worked equally well, but here the results are shown based on the shorter arc fits.

Figure 3-1 shows the range residuals from the Allan Park station from the two orbit fits. It should be noted in these and in most of the subsequent plots of residuals that a three sigma rejection filter for outliers was implemented in computing the mean and standard deviation or uncertainty. Figure 3-1 shows a very notable bias as well as a jump at about Day 001 of 1998. Figure 3-2 shows the range residuals from the Edmonton station for the two orbit fits and again a notable bias is seen, and there also appears a jump at Day 001, although it is not as obvious. By this means, range biases of –74 m and –47 m were determined for Allan Park before and after Day 001 of 1998, respectively. For Edmonton, range biases of 28 and 43 m were determined before and after Day 001, respectively. The uncertainties of the estimates are on the order of 6 m.

The next step was to apply these range bias corrections, check that the biases had converged, and see how well the Millstone data fit with the derived orbit. The 8-m error was kept for the Telesat range data. Figure 3-3 shows the Allan Park range data from the orbit fits after the calibration correction, and Figure 3-4 shows the Edmonton range data. Both the bias and the uncertainty seem to have stabilized; the latter appears to be a little better than the assigned 8 m.

The Millstone tracking data is shown to see how well it meshed with the orbit now using calibrated Telesat data. Figure 3-5 shows the Millstone azimuth, elevation, range, and range rate residuals over the entire 34-day period before the Telesat range data were incorporated, and Figure 3-6 shows the same over the period after the Telesat range data were used. Most important to note is that the Millstone residuals were not degraded when the Telesat range data were added which shows a good mesh of the data. There is perhaps a somewhat circular process going on, and the Millstone data should be expected to mesh since it helped determine the biases. But, the Telesat data were given appropriate weighting and there were sufficient amounts of it. So it also helped to determine the orbit. Since Millstone is calibrated using laser data from lower satellites, the exact calibration is not known for a geosynchronous satellite at the azimuth or elevation of Anik E1, and, therefore, the mean values and trends of the residuals to be expected are not exactly known. However, the specifications for Millstone are that the angle measurement error should be 5-10 mdeg, the range measurement error should be less than 6 m, and the range rate measurement error should be less than 3 mm/s. Figure 3-5 shows that Millstone errors from the two eighteen day orbits are within these specifications.

After this calibration, the true test was to evaluate the orbit quality. This was done throughout by examining the overlap of two orbits, which are considered independent except that they have some period in common, typically about 10% of the fit span length. To compute the overlap, ephemerides of ECI vectors were generated at 300 second spacing from both orbits over the common period. These vectors were then differenced and the differences transformed to along track (along the velocity vector), cross track (out-of-plane) and radial directions. Then the RMS (Root Mean Square) was computed for the differences projected into these components. The overlap for these orbits was examined with and without the Telesat data on Days 359-360. Figure 3-7 shows the overlap without the Telesat data. Figure 3-8 shows the overlap when Telesat data were used. Table 3-1 summarizes the RMS difference of the two orbits during the overlap period with and without the Telesat data. It should be noted that the error in the overlap is from both the overlapped orbits. One could generally consider the actual error of each orbit to be half the RMS difference of the overlap assuming equal error in both orbits on average. *But, here the RMS difference of the overlap will refer to the upper bound of the orbit error.*

**TABLE 3-1**

**Summary of RMS Differences of Overlapped Orbits on Days 359-360**

| | Along Track (m) | Cross Track (m) | Radial (m) |
|---|---|---|---|
| MH Only | 535 | 2471 | 263 |
| MH with Telesat | 33 | 122 | 17 |
| Telesat Only (uncalibrated) | 629 | 339 | 35 |
| Telesat Only (calibrated) | 106 | 126 | 9 |

There was a dramatic reduction of the cross track difference between the two orbit spans when the Telesat data were added. Cross track seems to be the predominant error component when just Millstone tracking data are used. The other two components improved as well. The overlap indicates orbit quality on the order of 130 m (RSS or root summed square of the three components) or better when the calibrated Telesat data were added.

The third line of Table 3-1 shows the overlap of the two orbit fits when only *uncalibrated* range data from the two Telesat stations were used. This would be the simplest way to use the CRDA range data, although presumably CRDA partner range biases could be used. The last line of Table 3-1 shows the overlap if only *calibrated* range data from the two Telesat stations were used. Here it would be assumed that the calibration biases were known apriori. In the Day 343-360 orbit fit using Telesat range data only, DYNAMO had difficulty solving for all three thrust components for the five thrusts of the 343-360 fit. In this case the values from the MH with Telesat orbit were used and otherwise values would have been required from the operator. There was only one maneuver during the Days 359-011 fit and this could be solved for.

The SBV data permitted an extra means of evaluating the orbit quality. The SBV measurements were not actually used in the orbit fit, but were compared with the Millstone-only orbits, and with the Millstone plus Telesat data orbits, and the resultant residuals used to show orbit quality and change in orbit quality. This use of the SBV data, therefore, is an external measure of orbit accuracy. Figure 3-9 shows the SBV measurements of right ascension and declination as compared with the Millstone-only orbit, and Figure 3-10 shows them compared with the combined Millstone and Telesat data orbit. The SBV residuals show significant improvement when the Telesat data were also used. The mean of the right ascension is reduced from 1.2 mdeg to 0.12 mdeg, and the sigma of the declination measurements is reduced from 2.4 mdeg to 0.4 mdeg. The expected mean of the SBV data should be 0.1-0.2 mdeg and the sigmas should range up to 1-1.5 mdeg [2]. With the addition of the Telesat data, the SBV residuals have means and sigmas better than 0.5 mdeg which indicates that SBV was providing better data than would be expected from its stated accuracy. And whether these SBV residuals are a result of measurement error or orbit error, they still provide an upper bound on the orbit accuracy. At the typical geosynchronous satellite distance from SBV, one mdeg is about 700 m. Therefore, these residuals gauge the orbit accuracy to roughly be at the two km level when only the Millstone data were used and to be roughly bounded at the 400-m level when the Telesat data were added. This result is consistent with the overlap analysis. The SBV data were also used to evaluate the orbits determined with calibrated Telesat only range data and similar results were obtained and further validate the accuracy of those orbits.

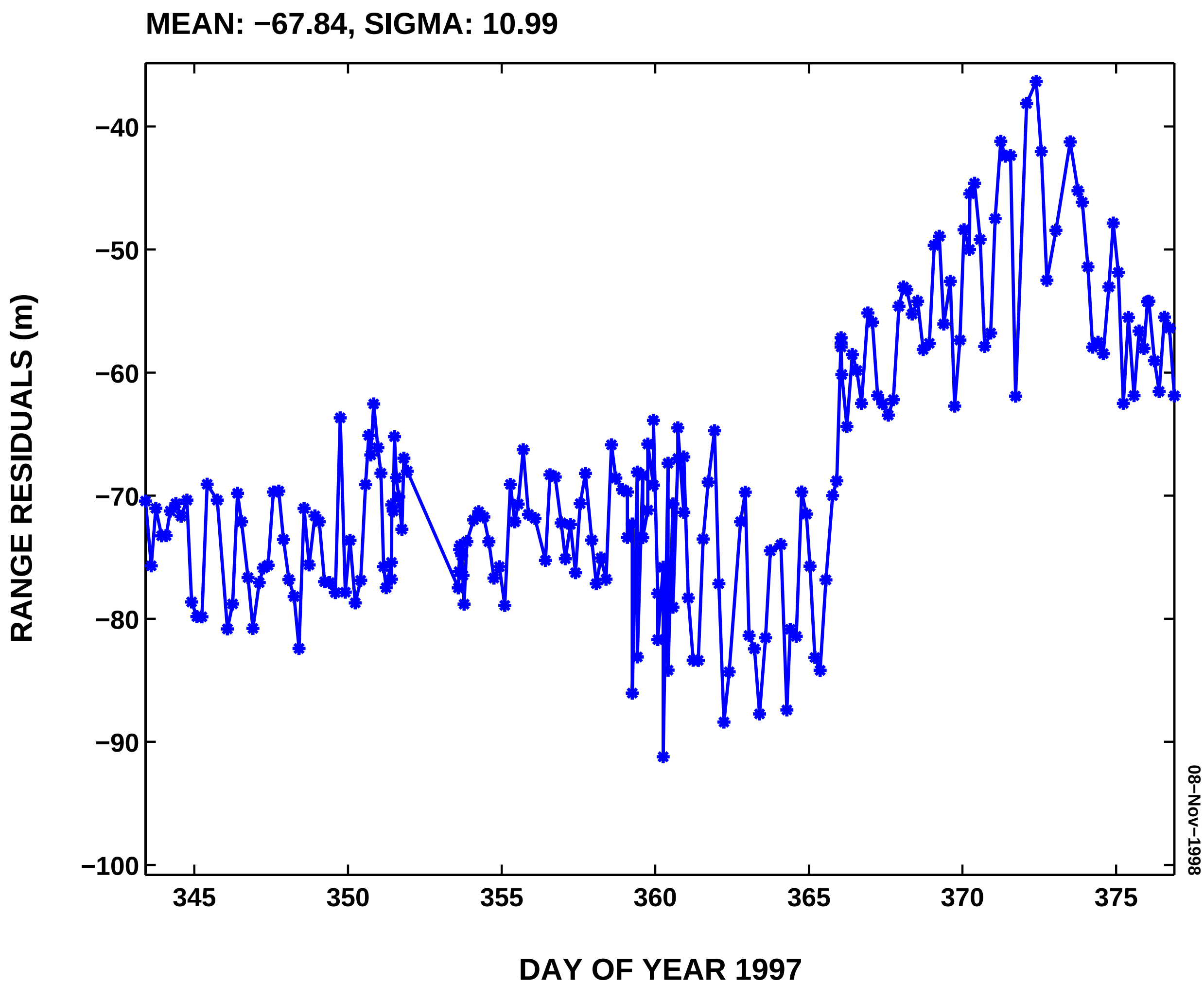


*Figure 3-1. Allan Park--Anik E1 range residuals on Days 343-376 before bias removed.*

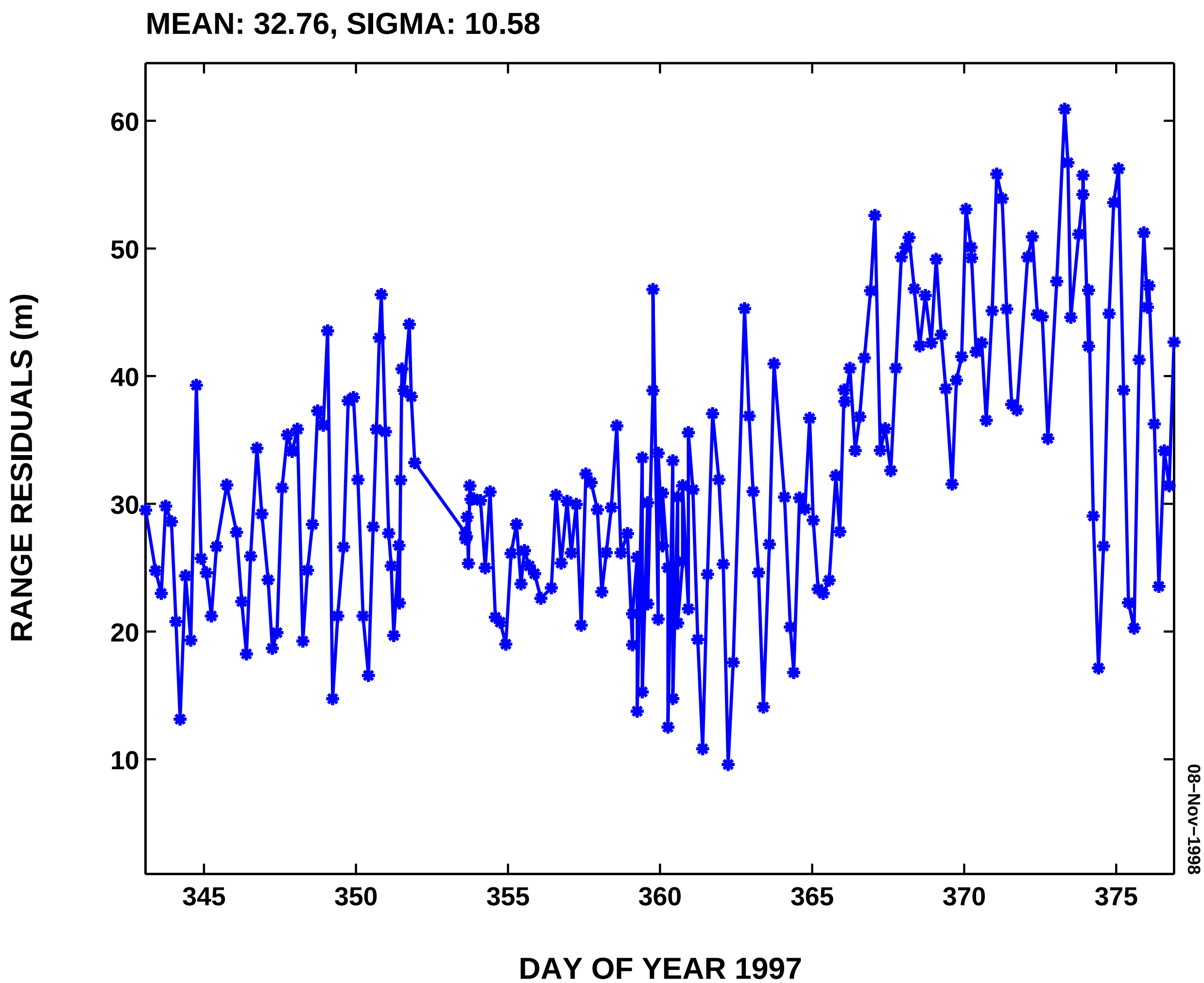


*Figure 3-2. Edmonton--Anik E1 range residuals on Days 343-376 before bias removed.*

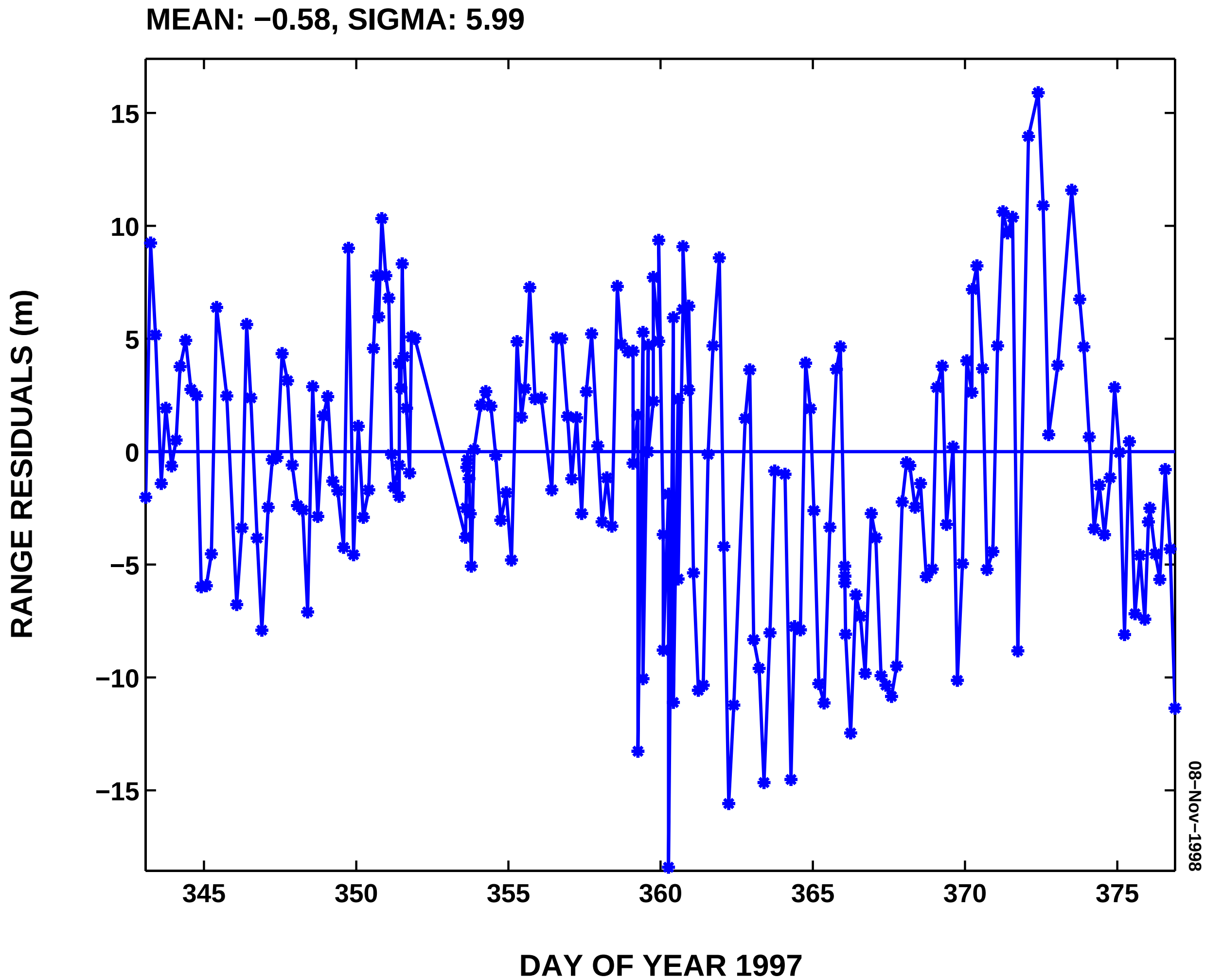


*Figure 3-3. Allan Park--Anik E1 range residuals on Days 343-376 with bias removed.*

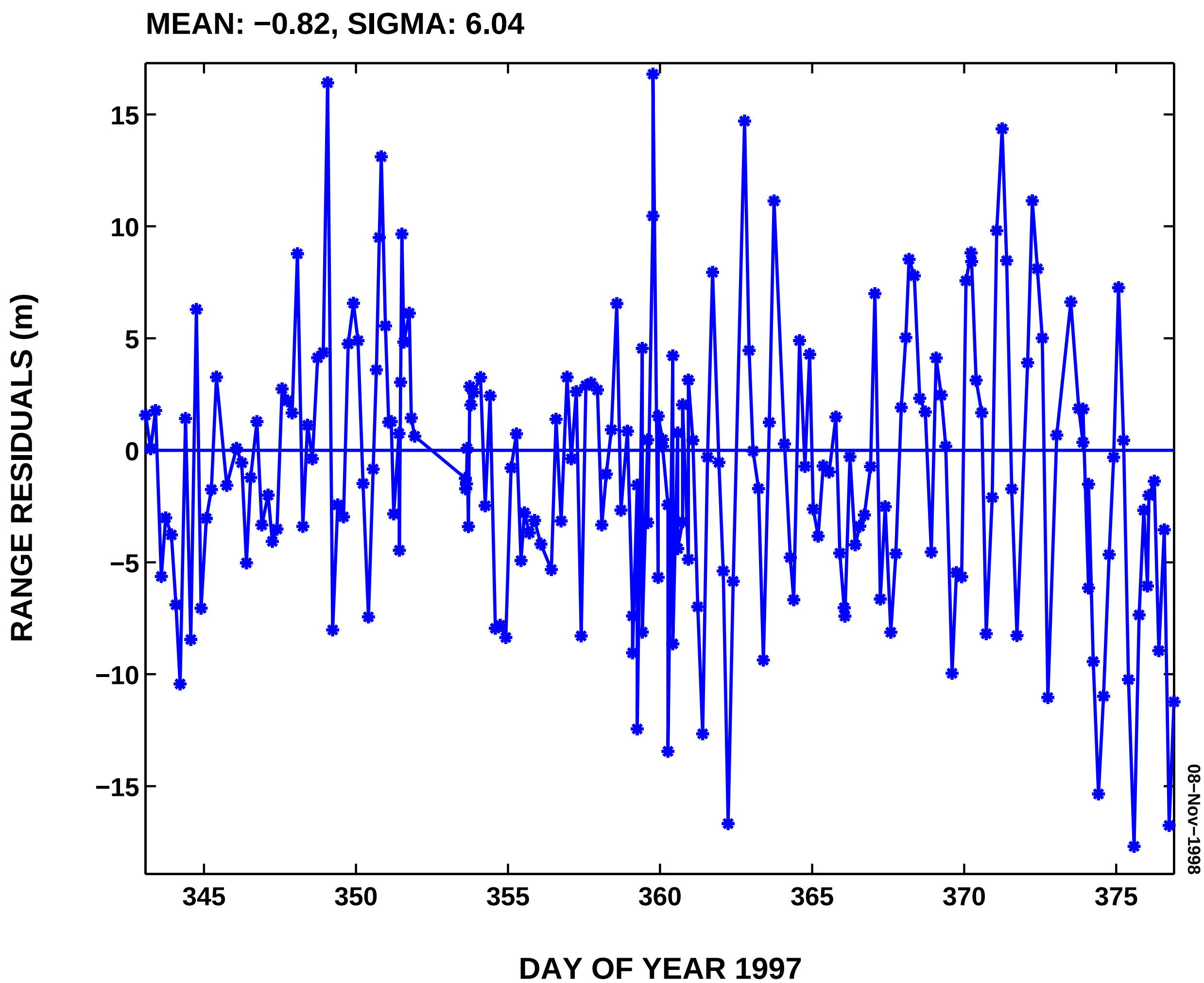


*Figure 3-4. Edmonton--Anik E1 range residuals on Days 343-376 with bias removed.*

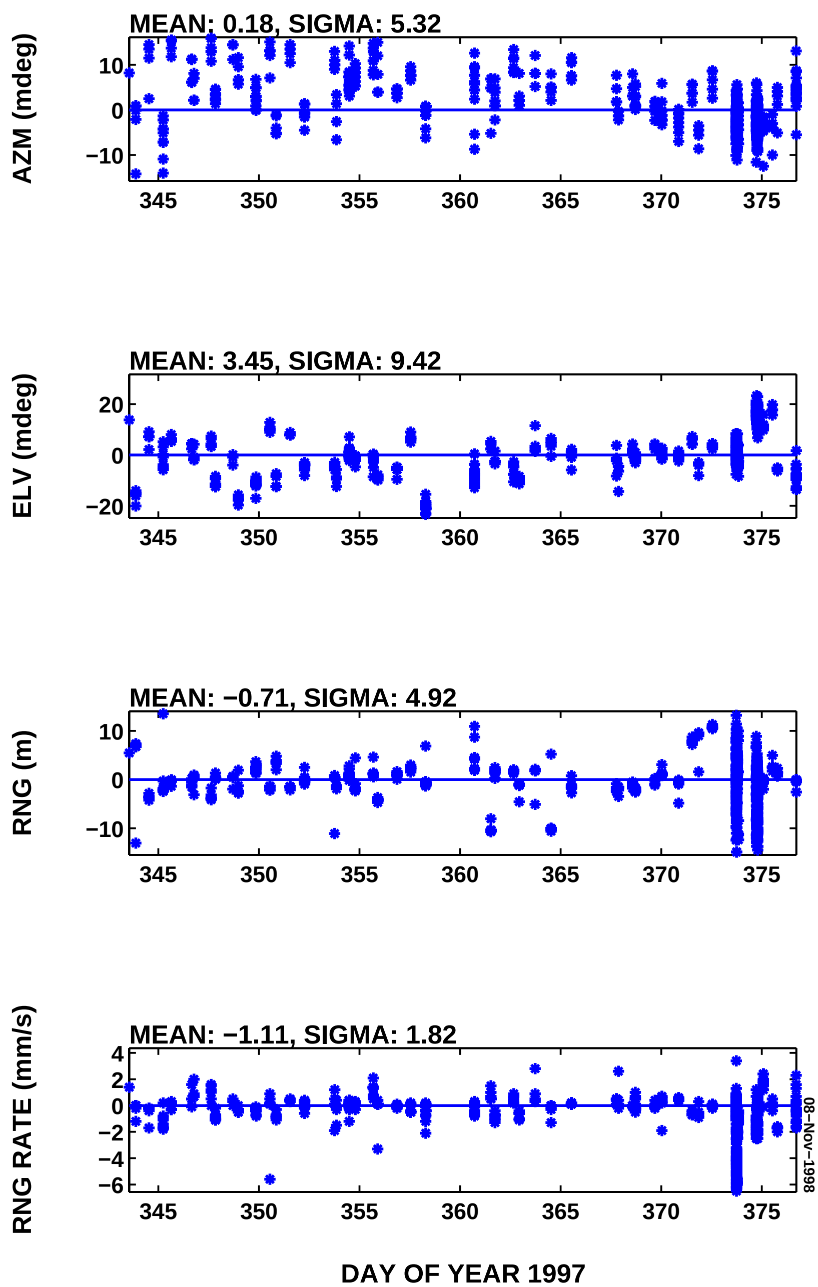


*Figure 3-5. Millstone measurement residuals for Anik E1 on Days 343-376 without Telesat range data in orbit fit.*

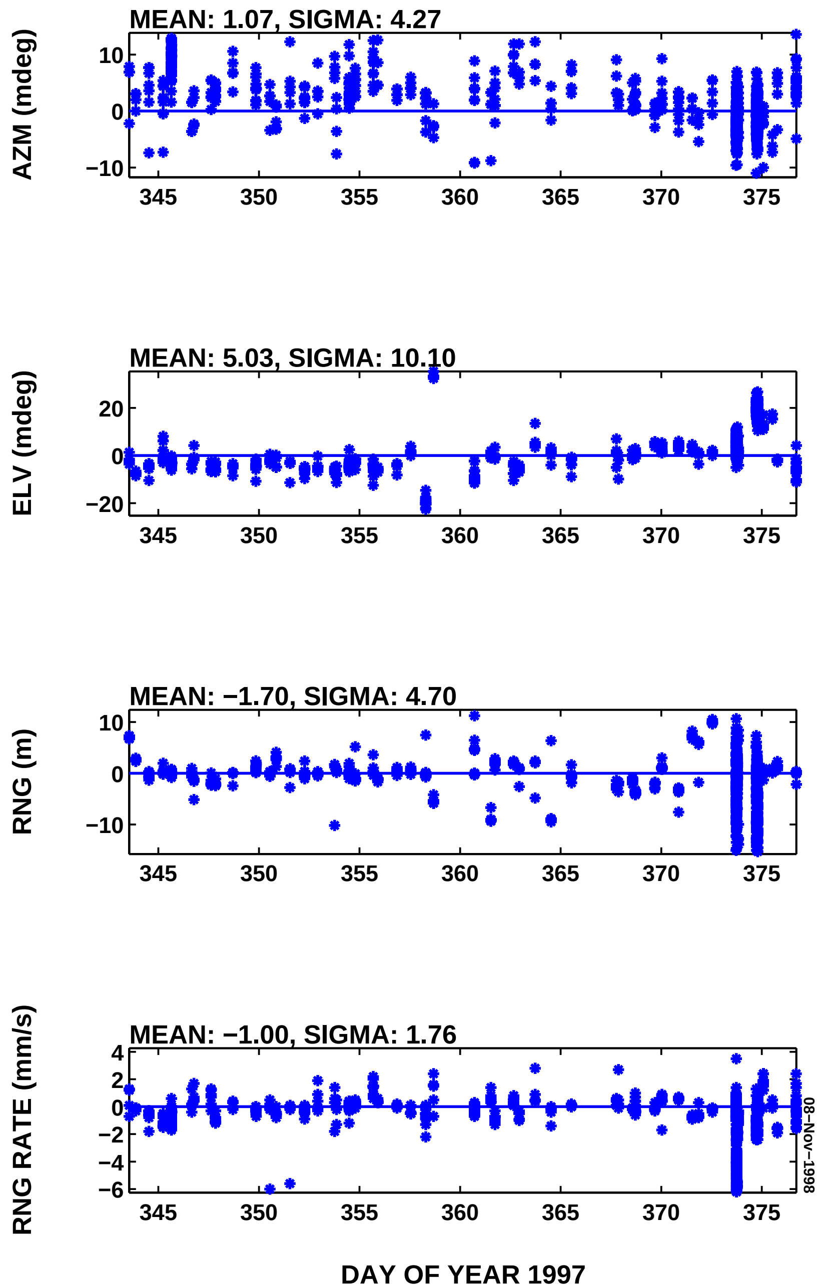


*Figure 3-6. Millstone measurement residuals for Anik E1 on Days 343-376 with Telesat range data in orbit fit.*

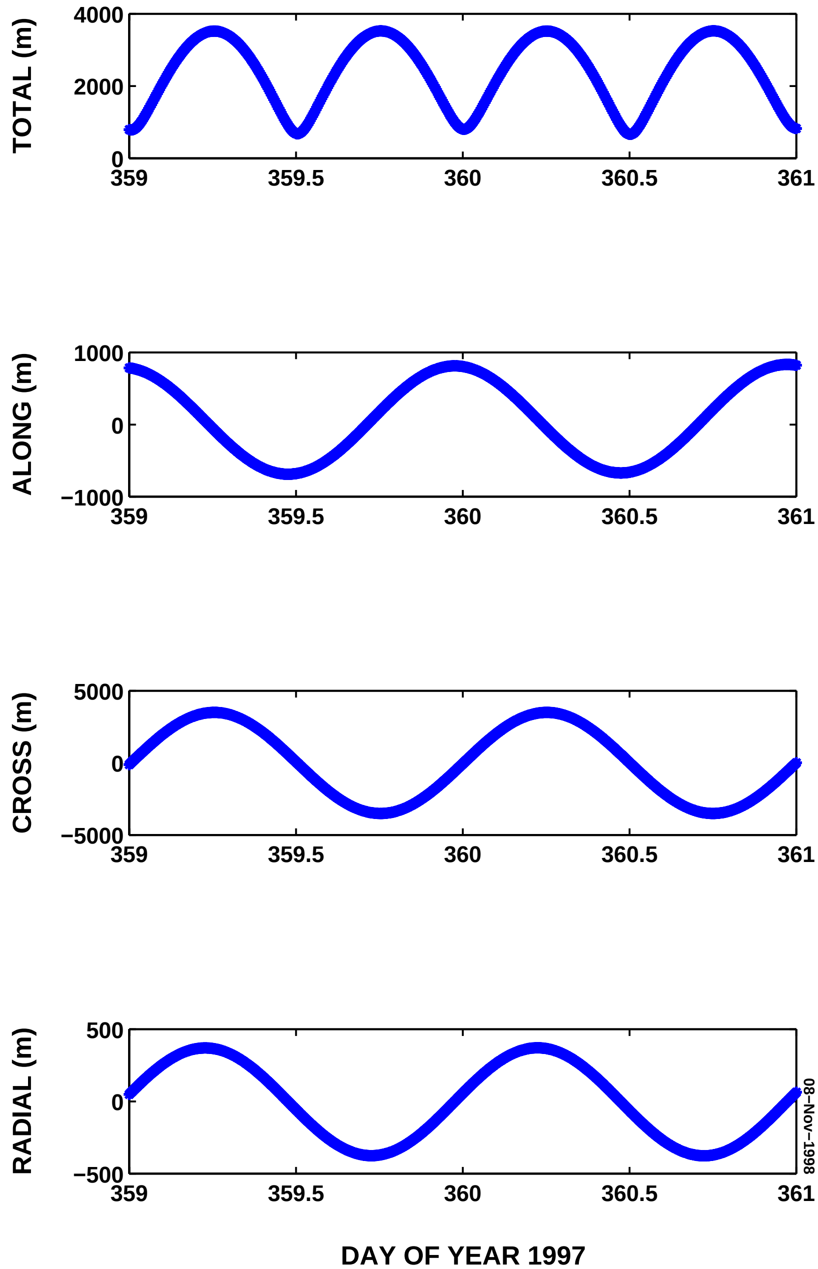


*Figure 3-7. Overlap accuracy assessment on Days 359-360 without Telesat range data.*

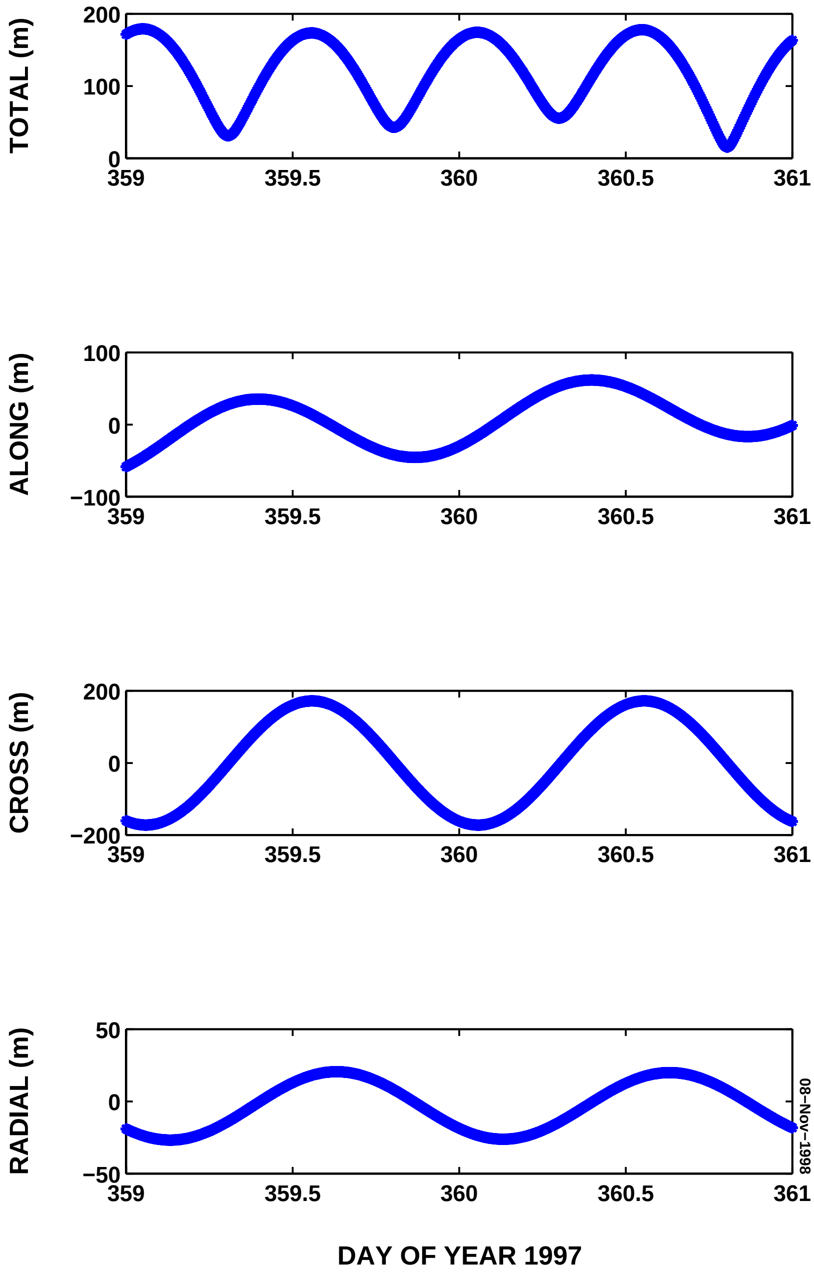


*Figure 3-8. Overlap accuracy assessment on Days 359-360 with Telesat range data.*

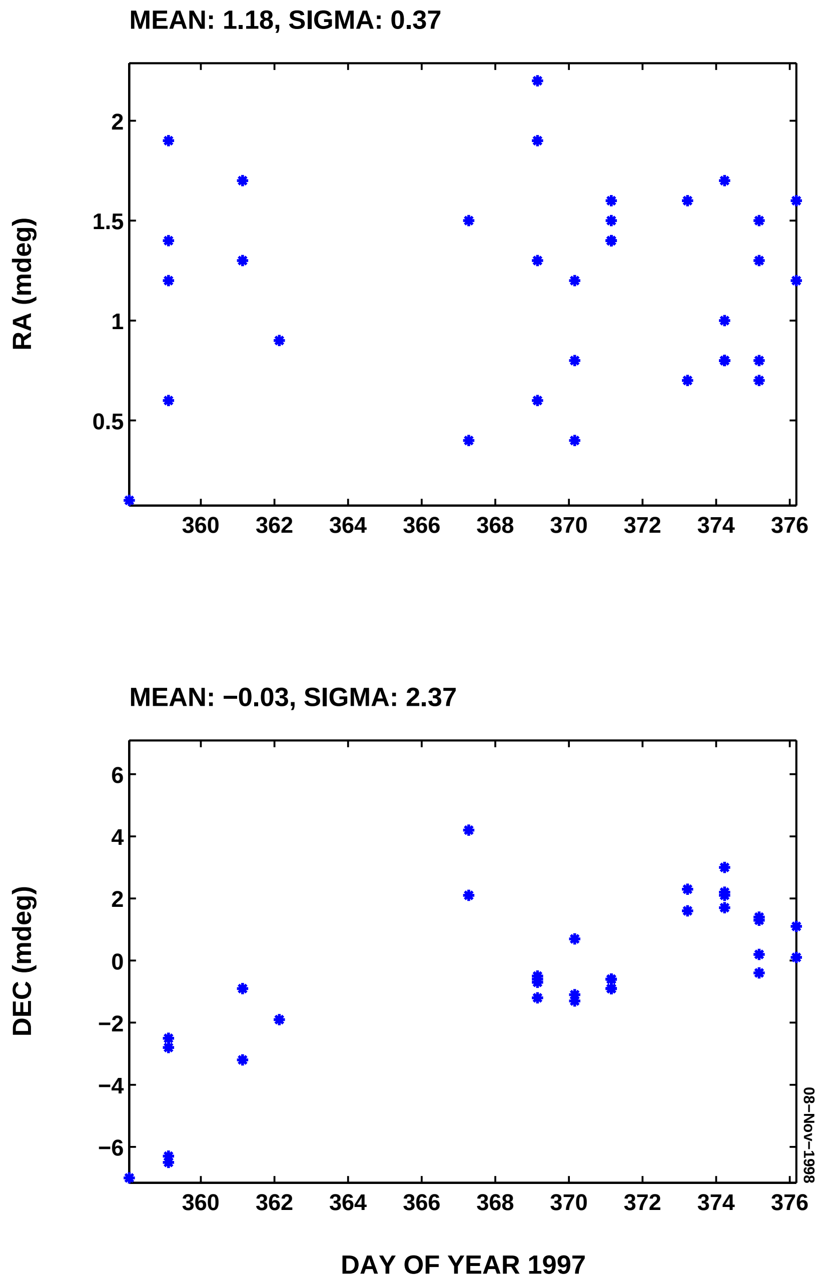


*Figure 3-9. SBV RA and DEC residuals for Anik E1 on Days 356-376 without Telesat range data.*

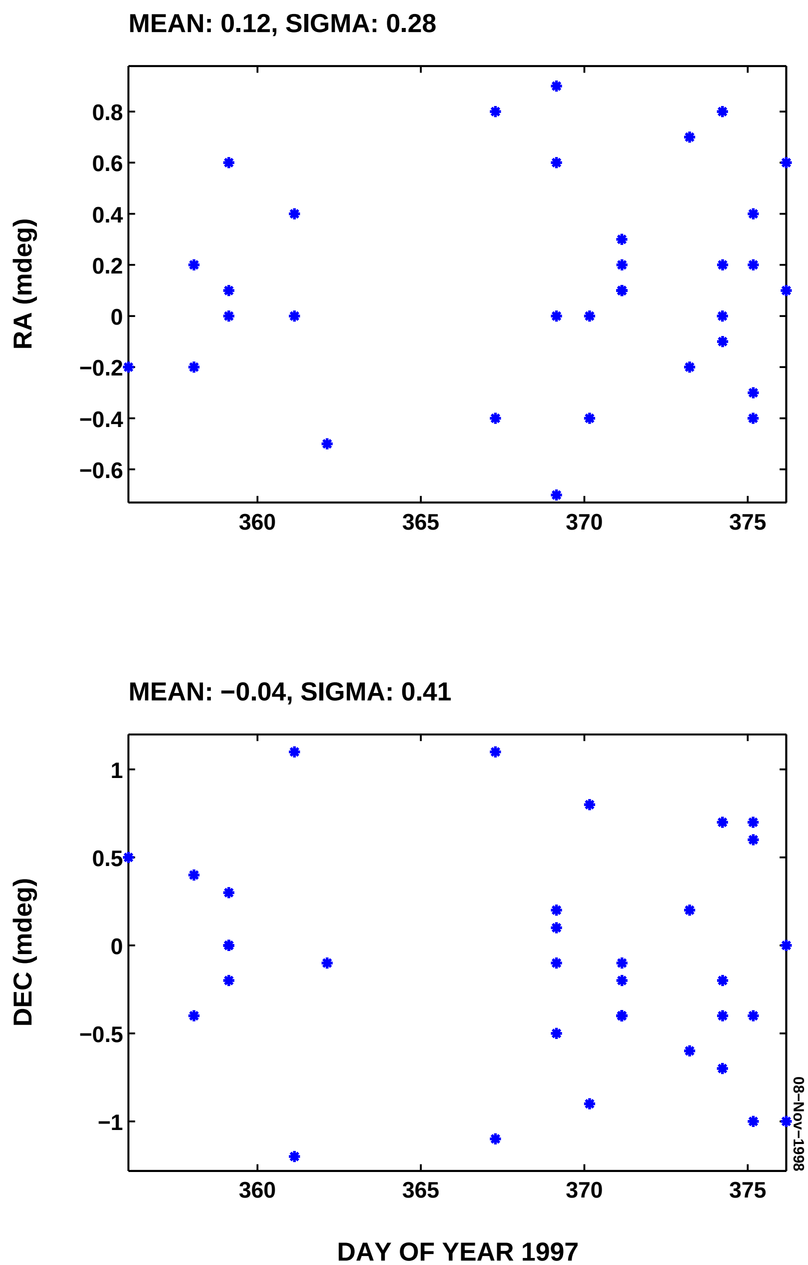


*Figure 3-10. SBV RA and DEC residuals for Anik E1 on Days 356-376 with Telesat range data.*

### 3.2 EXAMPLE 2: TELESAT CANADA, ANIK E1, JULY-AUGUST 1998

This example is similar to Example 1, but involves an ongoing monitoring of the calibration for operational use. Range data from Telesat Canada have been received for Anik E1 on a weekly basis since Day 190 of 1998. Calibration was initiated from Day 190, but this example will begin with data from Day 202 when Millstone began tracking Anik E1 for Telstar 401 encounter analysis. Millstone continued to track densely through to Day 229, providing one to two tracks per day of 5-15 measurements per track. Range data calibration for Anik E1 is continuing on an operational basis.

The goals of this example were:

- To re-establish the calibration for Anik E1 after a six month break in data reception.

- To provide another example of the orbit accuracy enhancement of Example 1 when Telesat range data are added.

- To initiate an operational maintenance of calibration for this satellite.

To re-establish the calibration, apriori range biases at Allan Park and Edmonton were adopted from the December-January data set as discussed above. An apriori measurement error of 8 m was again adopted. A period of 23 days was used to refine the calibration, from Days 203-225. There were a series of maneuvers following this period: on Days 226, 229, 230, 232, and 233. The Millstone data ended on Day 229. Since one goal of this example was to examine orbit accuracy enhancement using Millstone with the Telesat range data, and there were not enough Millstone data after Day 229 to fit through the maneuver on that day, the orbit fits ended with Day 225. This also gave two 12-day orbit fit spans that could be overlapped for accuracy assessment. These fits were over Days 203-214 (modeling through one maneuver) and 214-225 (modeling through two maneuvers) with the overlap on Day 214.

There were also SBV data with 11 tracks over the 23 days. An initial look at the accuracy of this data showed a mean of a few tenths of a millidegree, but a noise of about one mdeg. This data were not considered accurate enough to evaluate orbit accuracy at the few hundred meter level, as in the previous example. Therefore, the data were utilized in the orbit fit instead of just being compared against the orbit and would show how SBV data could enhance orbit accuracy.

The first thing to show are the Telesat range residuals over the fit Days 203-225 after the calibration had been established for Allan Park, with a range bias of -84 m determined and applied, and for Edmonton, with a range bias of -48 m determined and applied. These residuals are shown in Figure 3-11 and 3-12 for the two stations. The uncertainty in the bias estimates is about 9 m.

To assess orbit quality, three scenarios were considered: (1) Millstone-only tracking data, (2) Millstone and SBV tracking data, and (3) Millstone, SBV, and the Telesat range data. First, the measurement residuals are discussed for the various cases. Figure 3-13 shows the Millstone residuals in azimuth, elevation, range, and range rate for the Millstone-only orbit fit. There appears to be a significant bias in azimuth of -7 mdeg although the precision or noise of the azimuth and elevation are at the 3 to 5 mdeg level, whereas 5 to 10 mdeg is more typical. The range and range rate residuals are typical.

With the SBV data added, the Millstone residuals (not shown) have the following statistics: azimuth (mean = -6.8 mdeg, sigma = 4.7), elevation (mean = -0.2 mdeg, sigma = 4.7), range (mean = -0.1 m, sigma = 2.4), and range rate (mean = 0.3 mm/s, sigma = 1.3), and show that the Millstone data meshed in quite well. The SBV residuals are shown in Figure 3-14. The noise is at the one mdeg level expected value, and this is probably not due to orbit error, but is inherent in the measurements. When the Telesat range data were further added the Millstone and SBV residuals showed little change.

To show orbit accuracy, Table 3-2 summarizes the overlap on Day 214 from the Days 203-214 and 214-225 fits for the three cases. The addition of the SBV data with roughly one track every two days significantly reduces the cross track error as well as helps an already small radial error. The Telesat data then brings the orbit quality to about 200 m (RSS) or better. Figures 3-15 and 3-16 show the Telesat range residuals for Allan Park and Edmonton, respectively, for the two fits combined on each plot. The biases have not changed much with these shorter fits from the value obtained from the longer 23-day fit. Both the two-week and four-week fits are useful to determine the biases. As in the previous example, the overlap is also shown for the case when *uncalibrated* and *calibrated* (assuming the calibration biases to be known apriori) data from just the two Telesat stations were used. DYNAMO was able to solve for all thrust components when only Telesat data were used.

**TABLE 3-2**

**Summary of RMS Differences of Overlapped Orbits on Day 214**

| | Along Track (m) | Cross Track (m) | Radial (m) |
|---|---|---|---|
| MH Only | 475 | 1436 | 163 |
| MH with SBV | 423 | 586 | 80 |
| MH, SBV, Telesat | 149 | 133 | 20 |
| Telesat Only (uncalibrated) | 1314 | 1051 | 130 |
| Telesat Only (calibrated) | 28 | 47 | 14 |

There was one question as to the -7 mdeg bias in the Millstone azimuth measurements and whether it was an inherent measurement error or due to the orbit mismodeling. To check, Millstone data from the ongoing Telstar 401 tracking was examined and Figure 3-17 shows the azimuth residuals from Day 181 to 264. There also seems to be a negative bias. The azimuth of Anik E1 was 270 degrees and for Telstar 401 was 230 degrees. Although these are on different azimuth rails, the suggestion is still that the -7 mdeg bias is measurement error.

It is also noted that Figures 3-12 and 3-13 show a structure in the residuals with about a two-week period. Some of this remains in Figure 3-15, which shows the two 12-day fits on one plot. The structure is lost in Figure 3-16. This structure will be seen in other Telesat Canada data to be discussed. It could be due to maneuver mismodeling but the structure persists even with fit spans involving no maneuvers. It may be due to dynamic mismodeling, or perhaps radiation pressure, or some other unknown source.

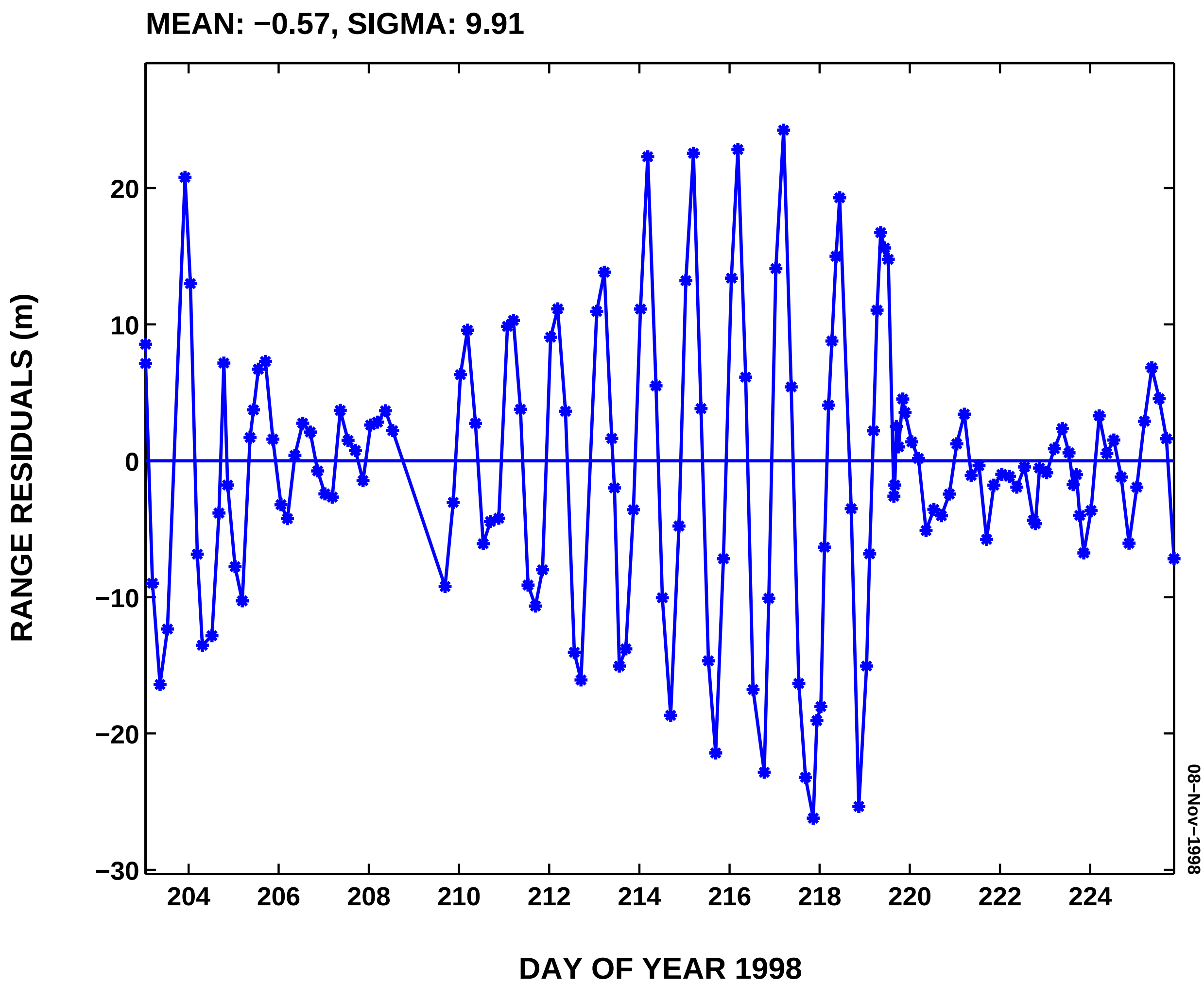


*Figure 3-11. Allan Park--Anik E1 range residuals on Days 203-225 with bias removed.*

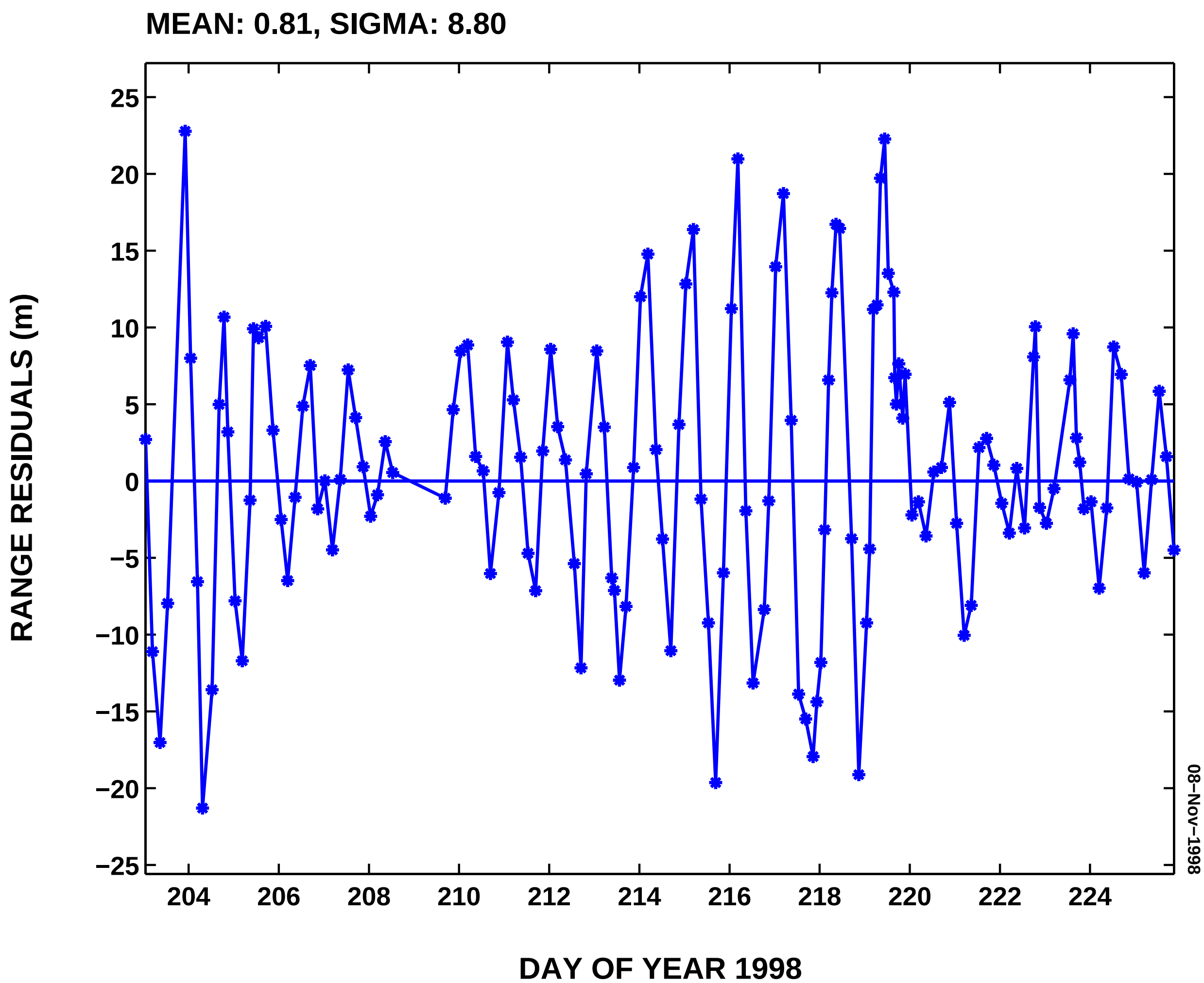


*Figure 3-12. Edmonton--Anik E1 range residuals on Days 203-225 with bias removed.*

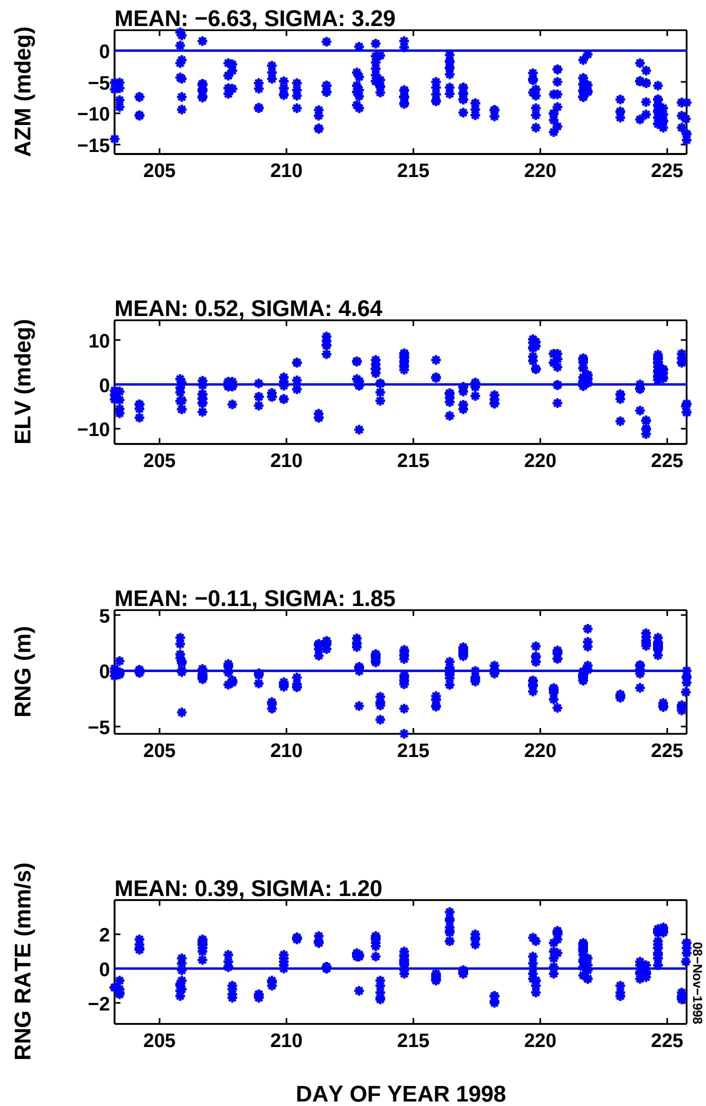


*Figure 3-13. Millstone measurement residuals for Anik E1 on Days 203-225 without Telesat range or SBV data in orbit fit.*

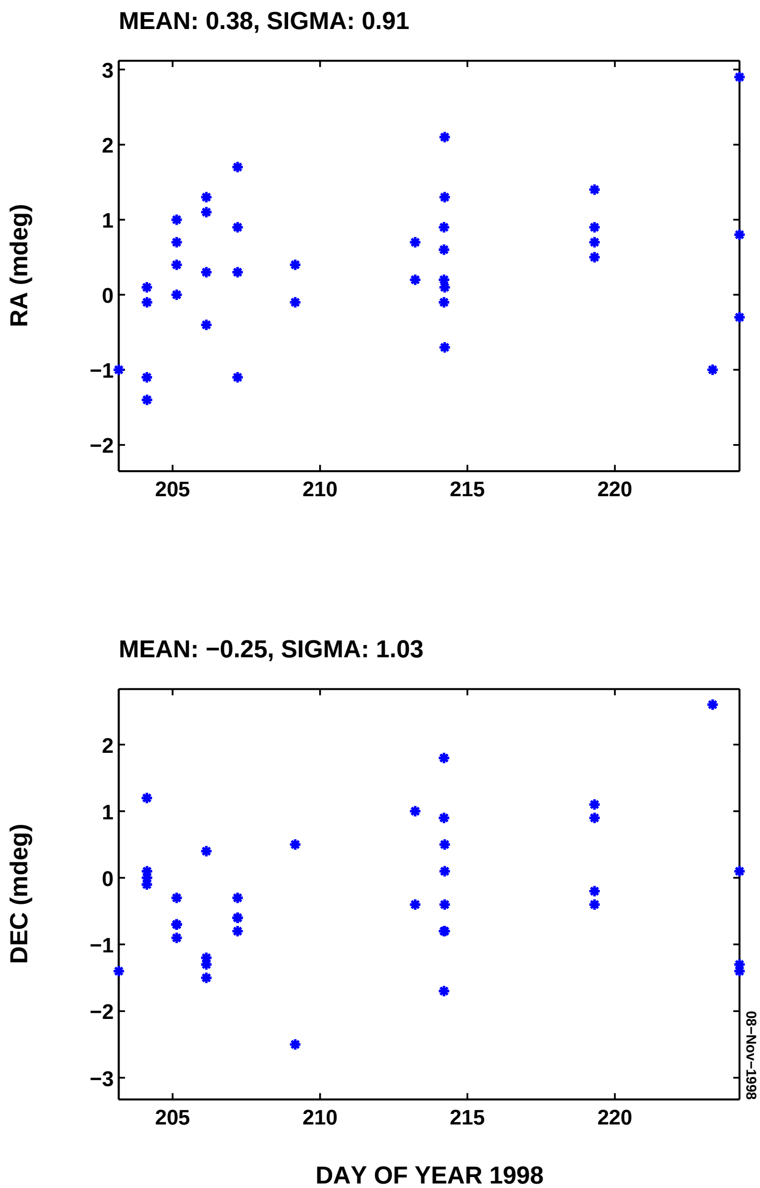


*Figure 3-14. SBV RA and DEC residuals for Anik E1 on Days 203-223 without Telesat range data.*

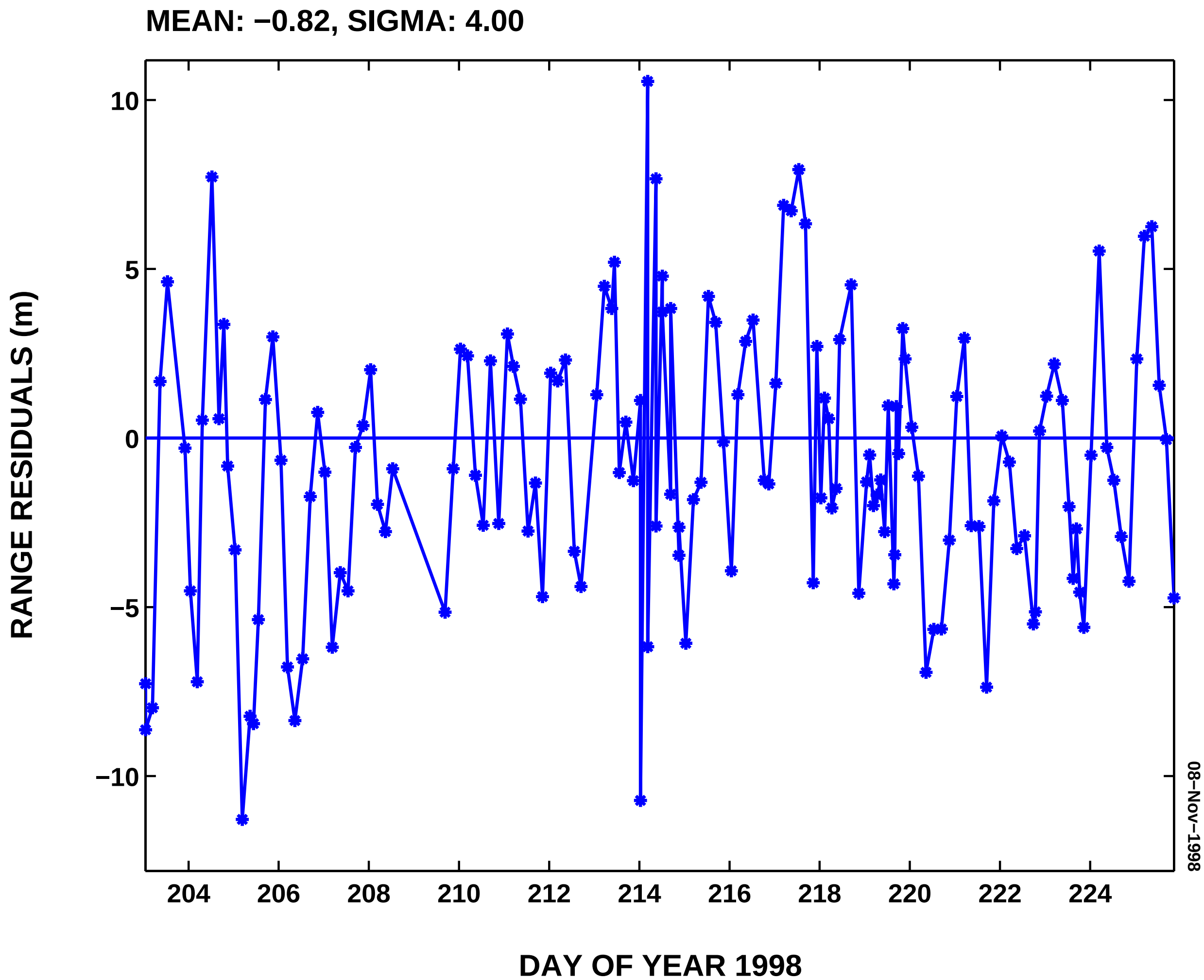


*Figure 3-15. Allan Park--Anik E1 range residuals from orbit fits over Days 203-214 and 214-225.*

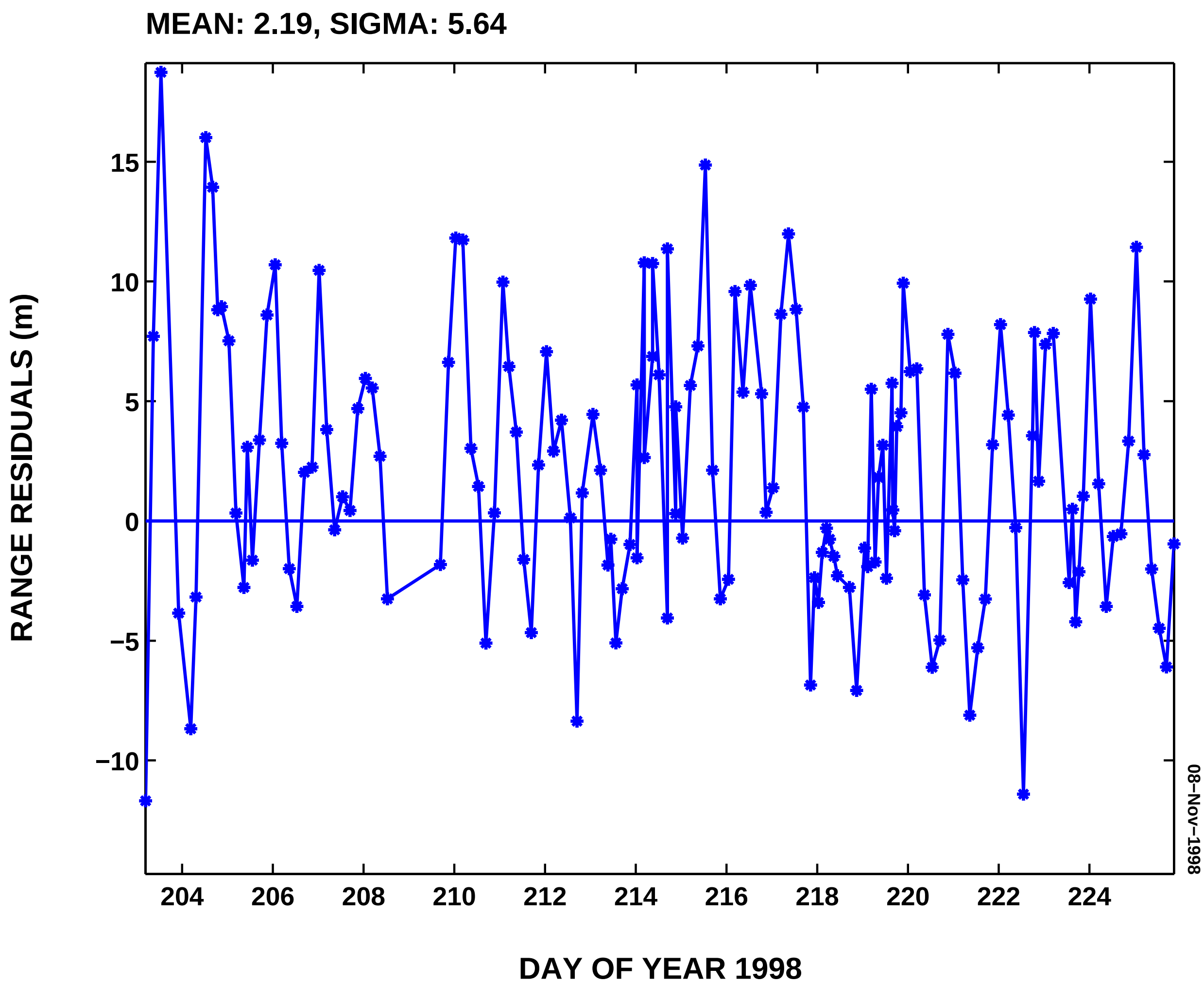


*Figure 3-16. Edmonton--Anik E1 range residuals from orbit fits over Days 203-214 and 214-225.*

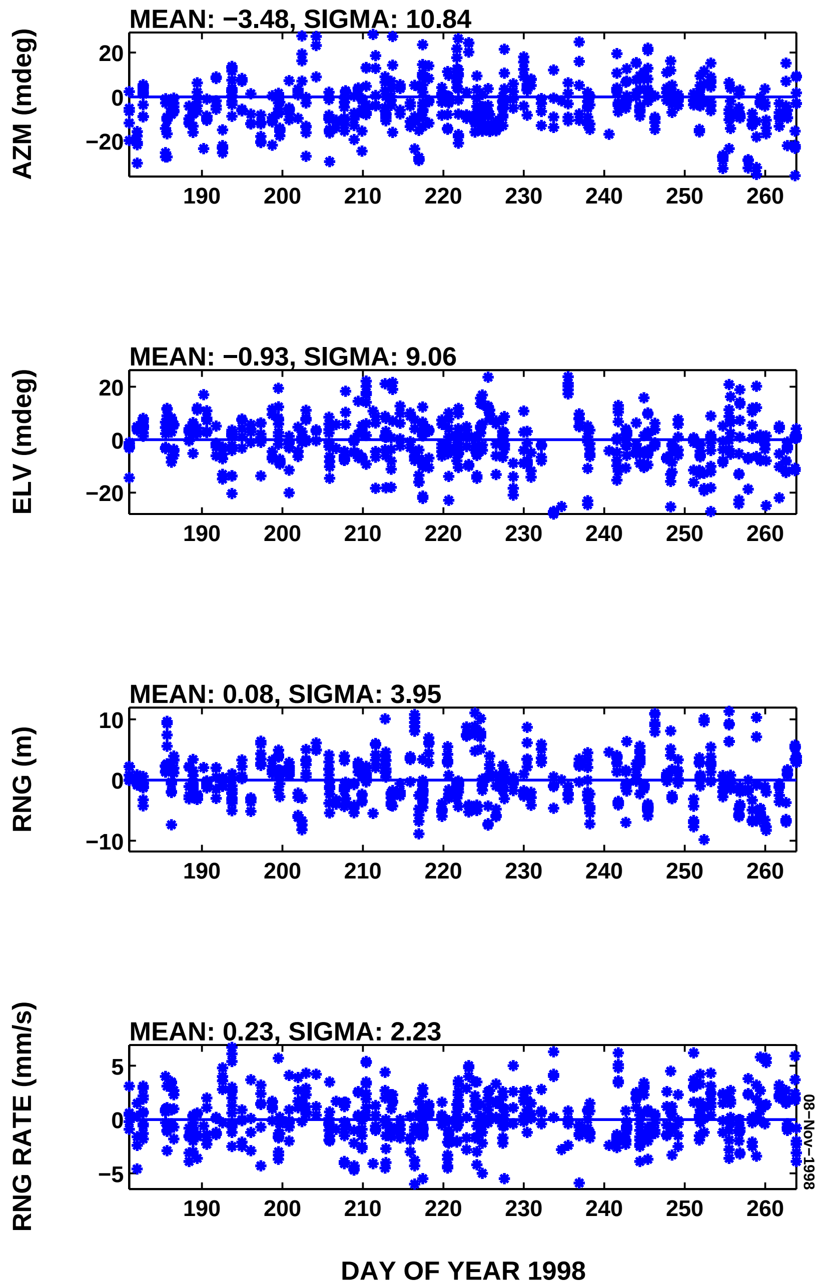


*Figure 3-17. Millstone measurement residuals for Telstar 401 on Days 181-263.*

### 3.3 EXAMPLE 3: SATMEX, SOLIDARIDAD 2, MAY-JUNE 1998

This data set consisted of data over a period of about a month plus dense Millstone tracking to support a Telstar 401 encounter. No SBV data were available. This example proved informative since when the SatMex data were compared with a Millstone (and other SSN data) orbit and not used in the orbit fit, there were large (200 m or more) diurnal errors in the SatMex range residuals. This was assumed to be due to orbit error, and it was interesting to see how the SatMex data could help and how well it would mesh with the Millstone data. Also, the distribution of the SatMex tracking data was different than for Telesat Canada. The Telesat Canada data received indicated that they tracked continuously every few hours from both stations. The SatMex data received indicated that they tracked densely for a day and a half or so from a station and then went a few days before tracking from that station again. There were actually only five such SatMex tracks in this analysis. The goals of this example, therefore, were as for the previous examples except that:

- There was a different distribution of SatMex tracking data.

- Both SatMex stations are far from Millstone.

SatMex provided a number of sample data sets and has provided data operationally on a routine basis. The data of interest in this example were from Days 129 to 153 of 1998. The SatMex tracking of Solidaridad 2 over this period consisted of data from three sites: Hermosillo B, Iztapalapa D, and Iztapalapa T-Tach. Hermosillo is located in Northwest Mexico and Iztapalapa is located in Southeast Mexico. There were three tracks from Hermosillo B and one each from the Iztapalapa sites with each track containing measurements taken as frequently as every minute. There were five maneuvers during this period.

An orbit fit over the entire 25-day period was first performed in order to determine the biases at the two stations. As mentioned, the SatMex data were initially unweighted in order to see how well a Millstone-only orbit could determine the SatMex range biases. There were 38 Millstone tracks over the 25-day period with 5-15 measurements per track. Residuals with a diurnal periodicity, and up to 200 or so meters, were seen. The accuracy of these Millstone-only orbits was examined by computing orbits over Day 129-141 (modeling through two maneuvers) and 141-153 (modeling through three maneuvers), and examining the overlap on Day 141. The RMS cross track component of the orbit differences was 3825 m, a little larger than is typically seen (although this is due to the orbit error in both fit spans). The Millstone residuals over these two fits are shown in Figure 3-18; the angle measurements were not as good as those for Anik E1 and appeared about a factor of two worse in the uncertainties. There are also large biases in both angle measurements and the range measurements were uncommonly noisy. As a check, the angle residuals for Telstar 401 over this period did not show angle biases of this nature. The larger orbit error may also have resulted from a poorer determination of the solve for thrust parameters. This size orbit error in the Millstone-only orbit was clearly causing the signature in the SatMex residuals when that data were compared with the Millstone orbit. Therefore, in order to calibrate it, the SatMex data were then weighted in the 25-day orbit fit and the biases and measurement error (for the purpose of weighting the data) determined iteratively. The biases at the two stations were determined to be 68 m for Hermosillo B and 64 m and 128 m for Iztapalapa D and Iztapalapa T-Tach, respectively. An apriori error of 4 m was adopted for weighting the data, and was also the uncertainty in the bias estimates. The final

SatMex residuals for Hermosillo B, Iztapalapa D, and Iztapalapa T-Tach over the Day 129-153 period are shown in Figures 3-19 through 3-21, respectively. The means and uncertainties look quite good although the residual structure is not random. The Millstone residuals from this joint fit are not shown, but have the following statistics: azimuth (mean = 10.0 mdeg, sigma = 13.5), elevation (mean = 8.7 mdeg, sigma = 9.8), range (mean = 4.3 m, sigma = 17.5), range rate (mean = 0.4 mm/s, sigma = 2.8), and show that the Millstone data have not been corrupted. The biases and uncertainties in the Millstone angle measurements did not improve significantly with the addition of the SatMex data, and the range uncertainty is still much larger than is usually seen.

To evaluate orbit accuracy, the SatMex data were included in the two fits mentioned above from Days 129-141 and 141-153. The resulting overlap on Day 141, with and without the SatMex data, is shown in Table 3-3. The calibration from the 25-day fit held up with the two shorter fits and their residuals are not shown.

**TABLE 3-3**

**Summary of RMS Differences of Overlapped Orbits on Day 141**

| | Along Track (m) | Cross Track (m) | Radial (m) |
|---|---|---|---|
| MH Only | 756 | 3825 | 352 |
| MH Plus SatMex | 708 | 863 | 76 |

The use of the SatMex range data did considerably improve the orbit quality especially in the cross track component. The orbit quality is on the order of one km (RSS). The level of orbit quality that the Telesat Canada data yielded was not achieved though. The SatMex data were very dense, but were in one and a half day tracks. The orbit fit over Days 129-141 had just two SatMex tracks and the Days 141-153 fit had just three SatMex tracks. Also, perhaps the maneuvers could not be fit as well. The results seem impressive nonetheless given that just these few days of dense SatMex tracking can so greatly improve the cross track error. With just five tracks of range data, no orbits were computed using just the uncalibrated or the calibrated SatMex data.

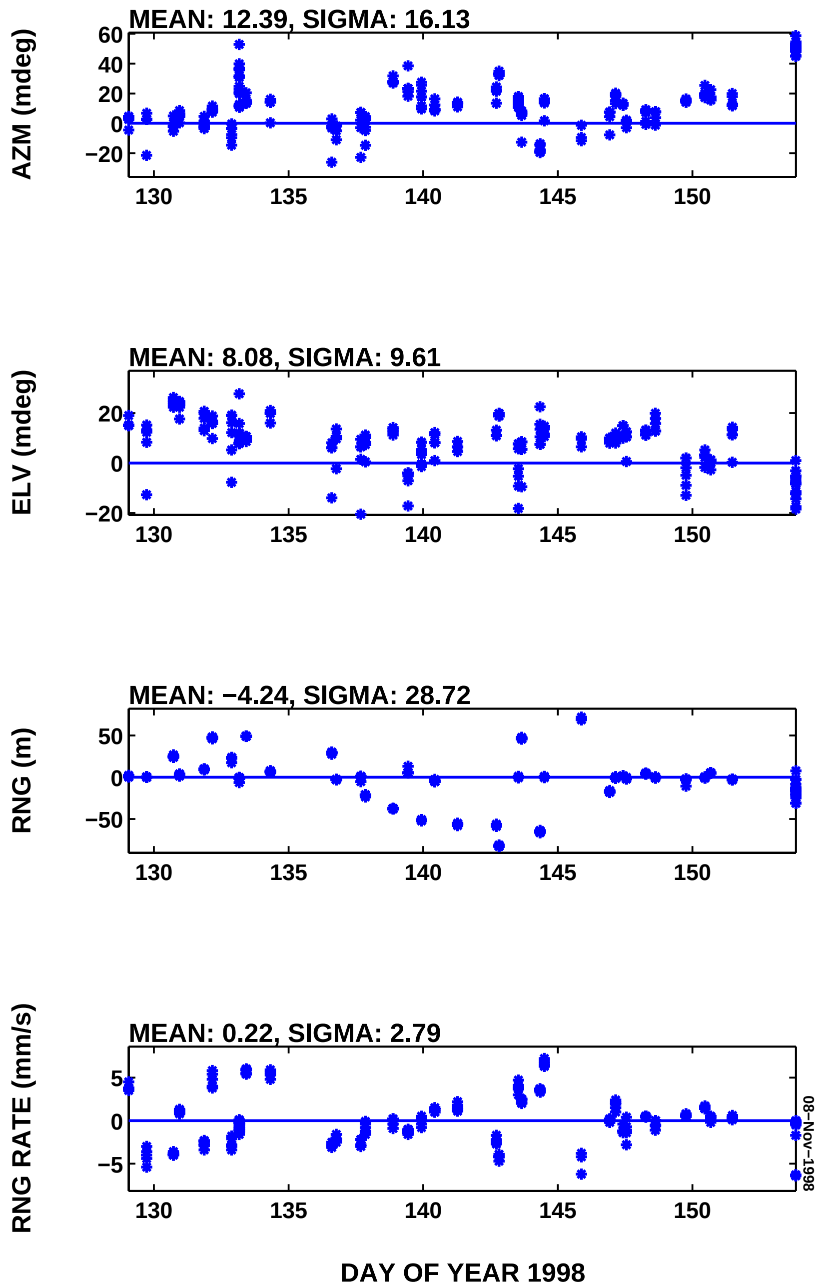


*Figure 3-18. Millstone measurement residuals for Solidaridad 1 on Days 141-153 with SatMex range data.*

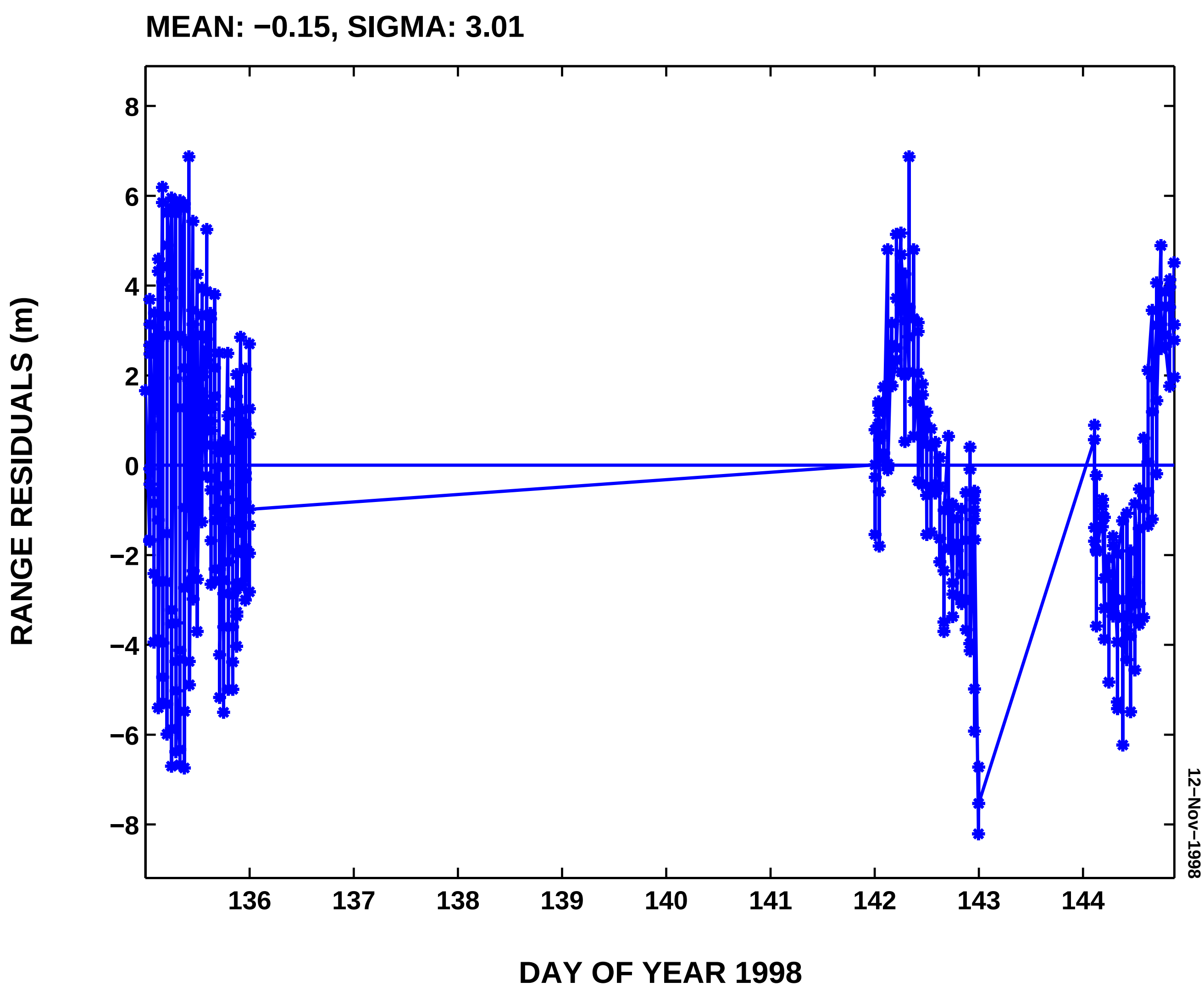


*Figure 3-19. Hermosillo B--Solidaridad 1 range residuals through Days 135-144 with bias removed.*

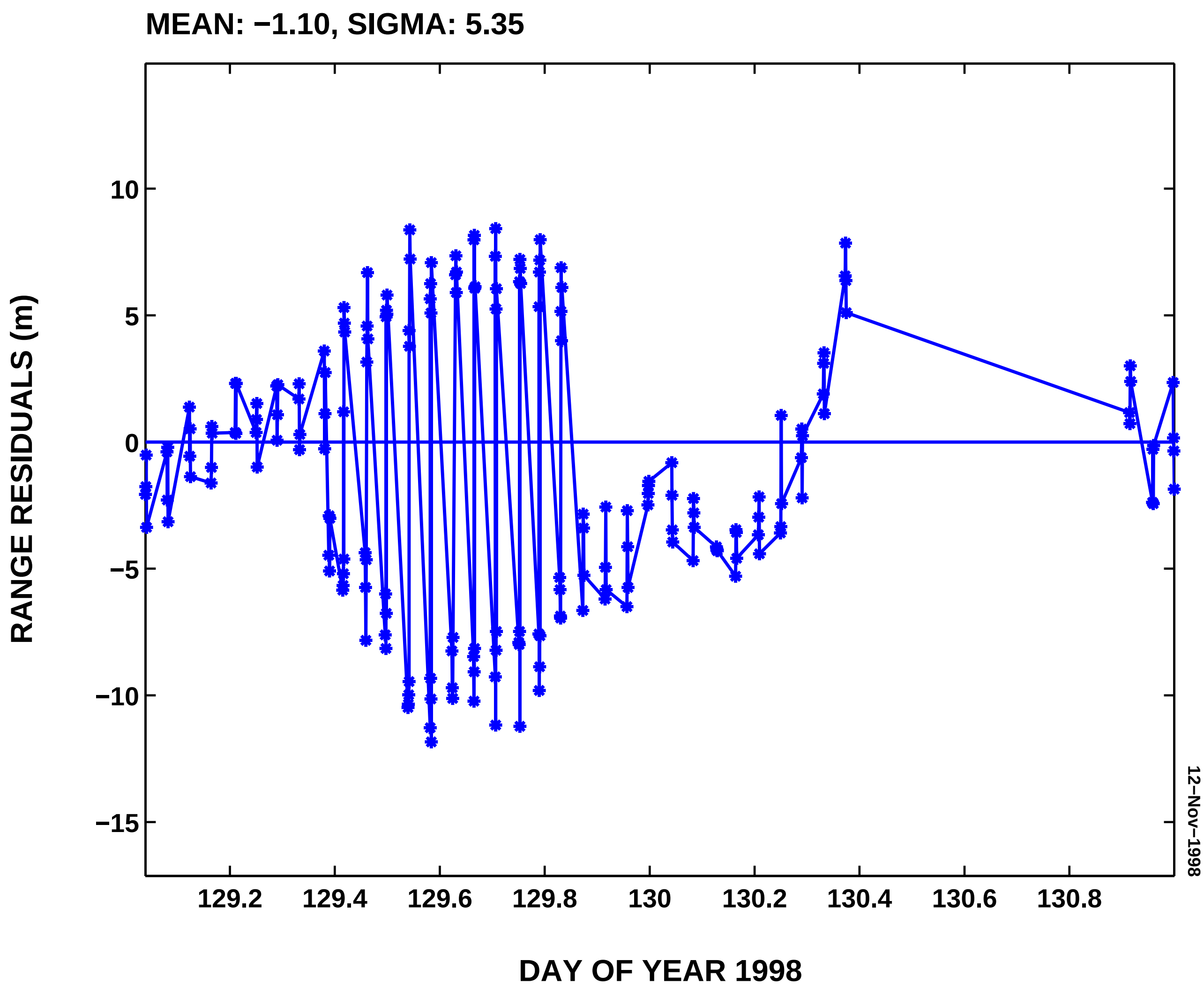


*Figure 3-20. Iztapalapa D--Solidaridad 1 range residuals on Days 129-130 with bias removed.*

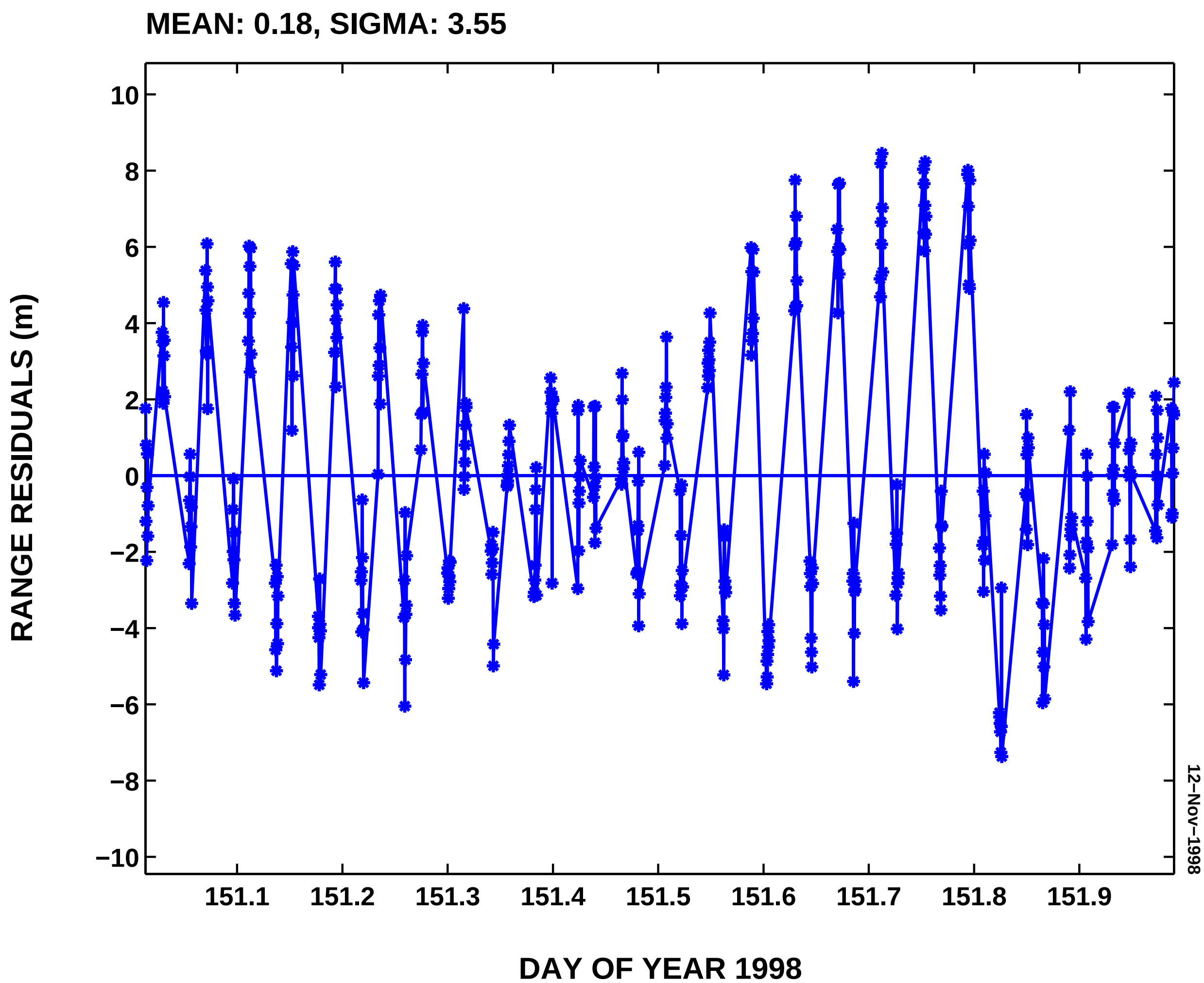


*Figure 3-21. Iztapalapa T-Tach--Solidaridad 1 range residuals on Day 151 with bias removed.*

### 3.4 EXAMPLE 4: PANAMSAT, GALAXY IV, MAY-JUNE 1998

This data set consisted of data over a period of 24 days, actually when Galaxy IV was being boosted. In this case, there was a less dense set of Millstone tracking since this was not an encounter period with Telstar 401. The source of non-PanAmSat data was just a few (9) Millstone tracks and whatever other nominal Space Surveillance Network data that were available. This case is therefore important since it shows the calibration and capability of the CRDA range data when there is just the nominal source of SSN data that is routinely available plus some Millstone tracking. The more sparse data can assist in determining a rougher calibration of the range data so that it all fits together as well as possible to obtain a potential improvement in orbit quality.

The PanAmSat range data were over the period of Days 131-154 of 1998. The range data spacing was a measurement every two to three hours, and the data were continuous over the period. There were six maneuvers. The maneuver thrusts are generally in all three components: east-west, north-south, and radial, although the north-south or east-west dominates depending on the type of maneuver.

To determine the range biases in the PanAmSat data, an orbit fit using the available Millstone and other SSN data and the PanAmSat data were computed over the entire span of Days 131-154. The PanAmSat data were given an apriori error of 16 m as indicated by PanAmSat. The bias estimation was an iterative process, and the biases finally converged to the best values that could be determined. The values computed were -42 m for Spring Creek, NY, and -78 m for Fillmore, CA. The Spring Creek value is close to the -46 m value indicated by PanAmSat, and the Fillmore value is close to their -85 m value. They agree within the uncertainties of the bias estimates, which were about 15 m for Spring Creek and 25 m for Fillmore. All three thrust components were solved for, but the primary thrust component in each case that was recovered was close to the PanAmSat Delta V (velocity). The residuals for Spring Creek, NY, and Fillmore, CA, are shown in Figures 3-22 and 3-23, respectively. The residuals seem random with no notable structure. The means are non-zero, but the biases could not be better determined. The large sigmas are presumably due to difficulty fitting the maneuvers to better than the 100 m level and this affects the uncertainty in the bias estimate. The sigmas are also on the order of the measurement error of 16 m indicated by PanAmSat. Remember that there are only nominal SSN data with some Millstone tracking, and that the biases had to be determined while simultaneously fitting the maneuver thrusts.

The maneuvers were on Days 134, 136, 148, 150, and 151. To avoid fitting through these maneuvers, an orbit fit was computed over Days 137-147 and confirmed the above biases to 5 m.

To determine orbit quality, two fit spans were computed with overlap. These were over Day 131-143 (modeling through three maneuvers) and 142-154 (modeling through three maneuvers) yielding two 13-day fits. The residuals are shown in Figures 3-24 through 3-27 for the two orbit fits and the two stations. The nine tracks of Millstone residuals are shown in Figure 3-28. The distribution of Millstone tracking is not very uniform over Days 131-148. For comparison, orbits were also computed with just the Millstone and other SSN data. Without the PanAmSat range data, the maneuvers over the span of Days 142-154 could not be estimated nor an orbit determined. There was just one Millstone track over this period. Therefore, the only overlap of interest is that on Days 142-143 when the PanAmSat data were added. Table 3-4 shows the overlap quality.

**TABLE 3-4**

**Summary of RMS Differences of Overlapped Orbits on Days 142-143**

| | Along Track (m) | Cross Track (m) | Radial (m) |
|---|---|---|---|
| MH Plus PanAmSat | 201 | 135 | 24 |
| PanAmSat Only (uncalibrated) | 1423 | 1395 | 152 |
| PanAmSat Only (calibrated) | 202 | 658 | 51 |

This process led to an orbit accurate to about 250 m (RSS), which is quite good. And it yielded biases close to those used by PanAmSat. This example represents a scenario when nominal SSN tracking plus a few Millstone tracks are available. The third line of Table 3-4 shows the overlap of orbits derived from just *uncalibrated* and *calibrated* (assuming the calibration biases to be known apriori) PanAmSat data. DYNAMO had difficulty solving for all thrust components of the three maneuvers when only the PanAmSat data were used. Therefore values were adopted from the MH plus PanAmSat orbit fit. The PanAmSat only results are larger than expected and may be reflective of errors in the determination of the range biases or the thrust parameters with the more sparse Millstone data.

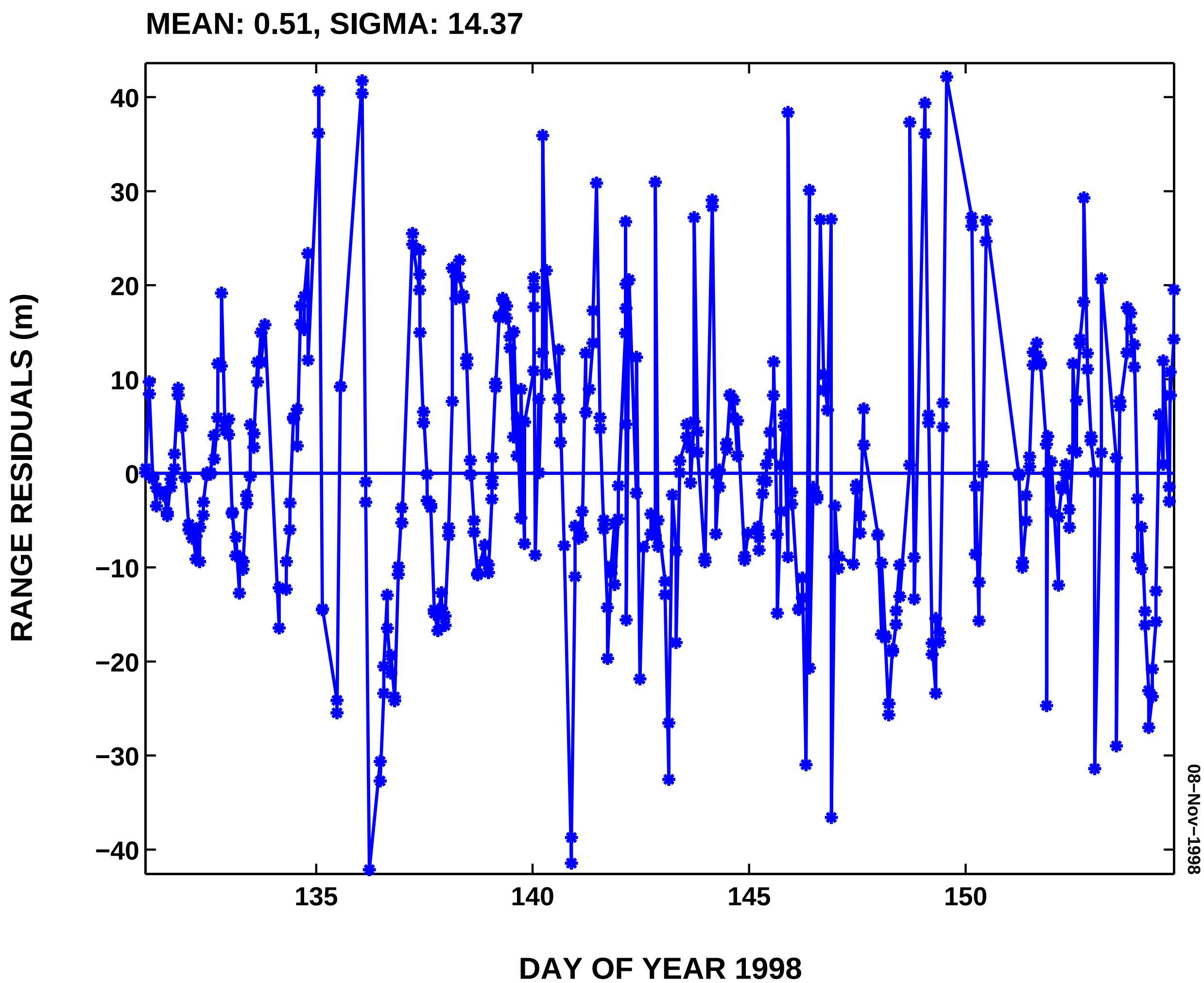


*Figure 3-22. Galaxy IV--Spring Creek range residuals on Days 131-154 with bias removed.*

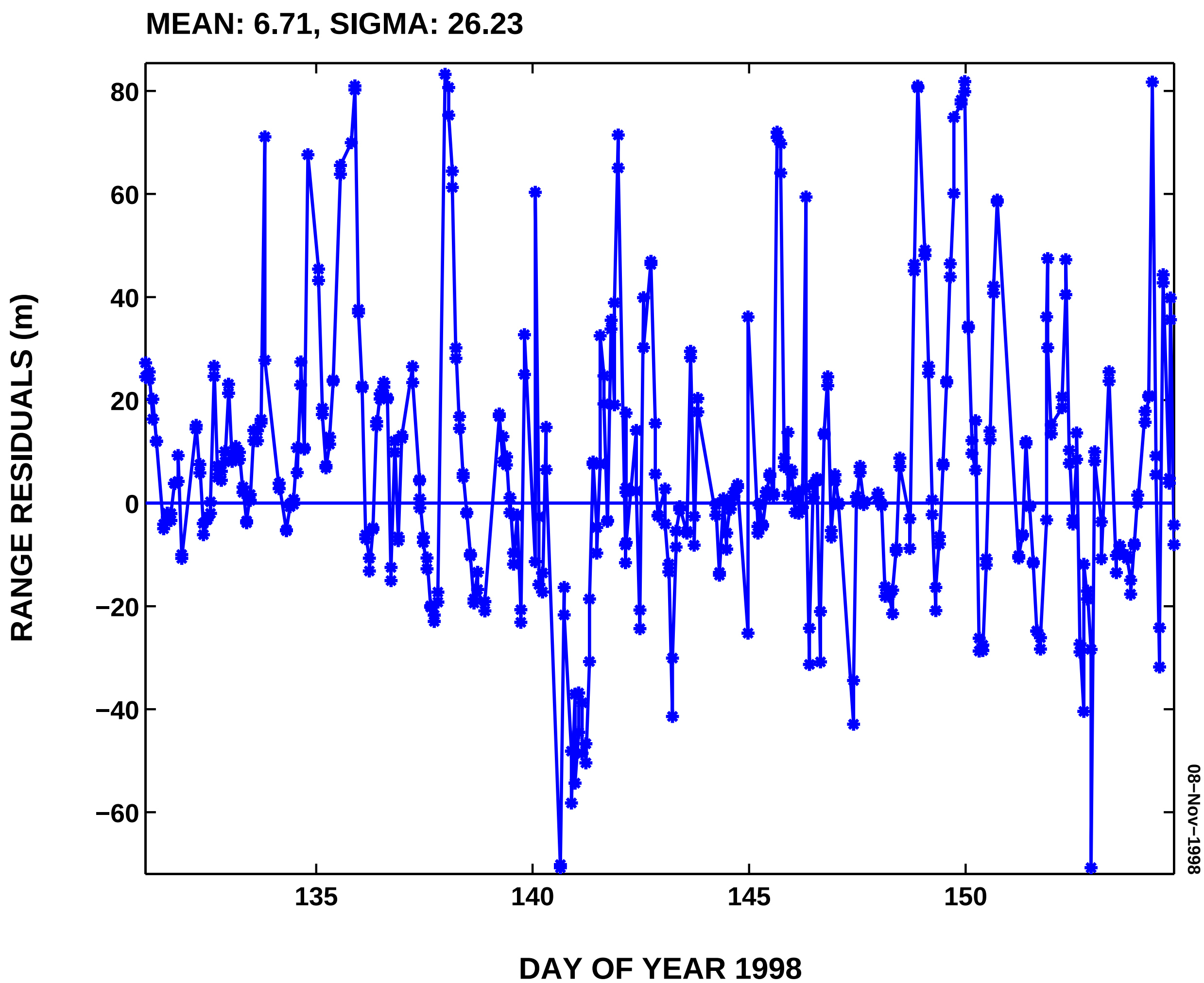


*Figure 3-23. Galaxy IV--Fillmore range residuals on Days 131-154 with bias removed.*

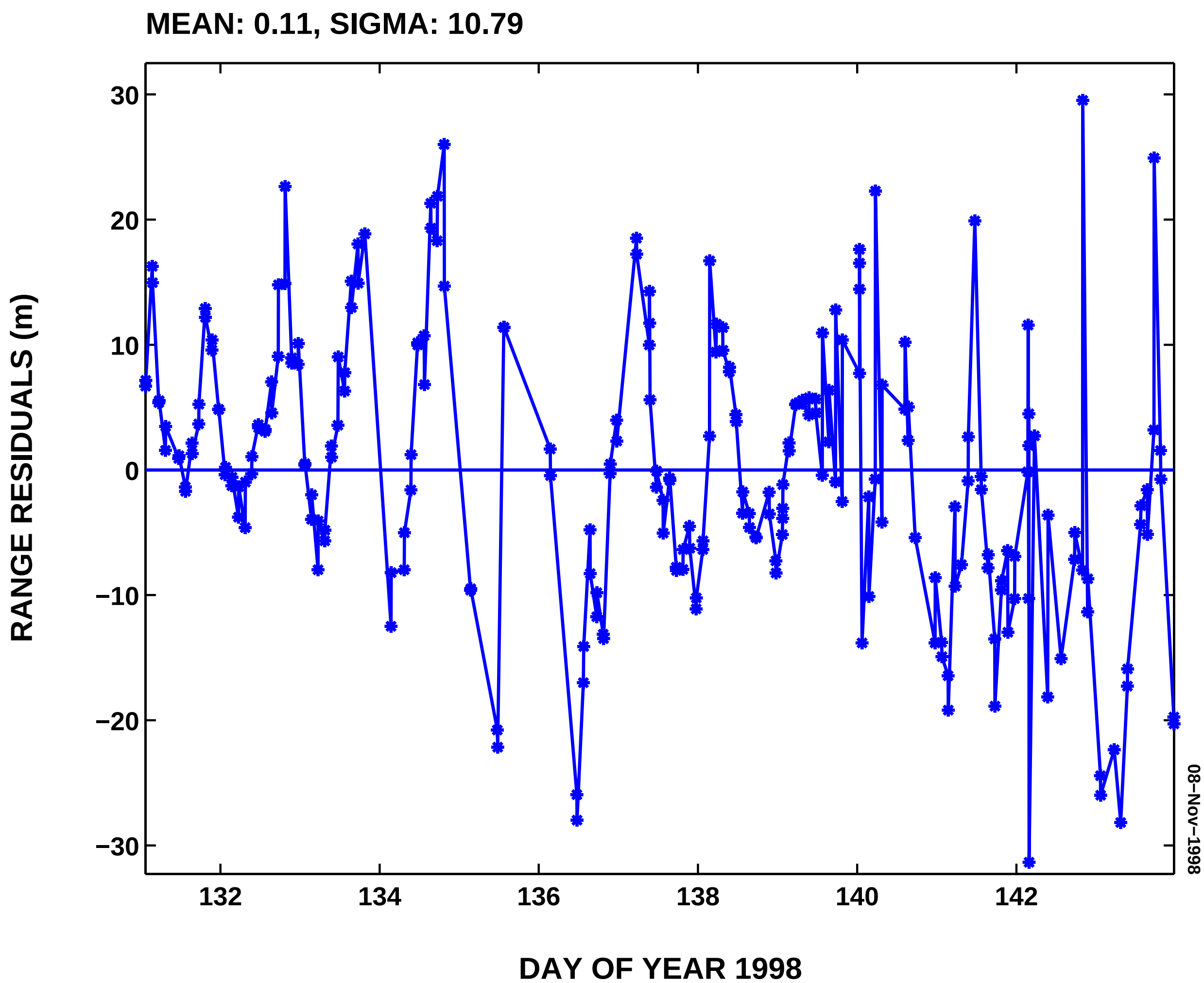


*Figure 3-24. Galaxy IV--Spring Creek range residuals on Days 131-143 with bias removed.*

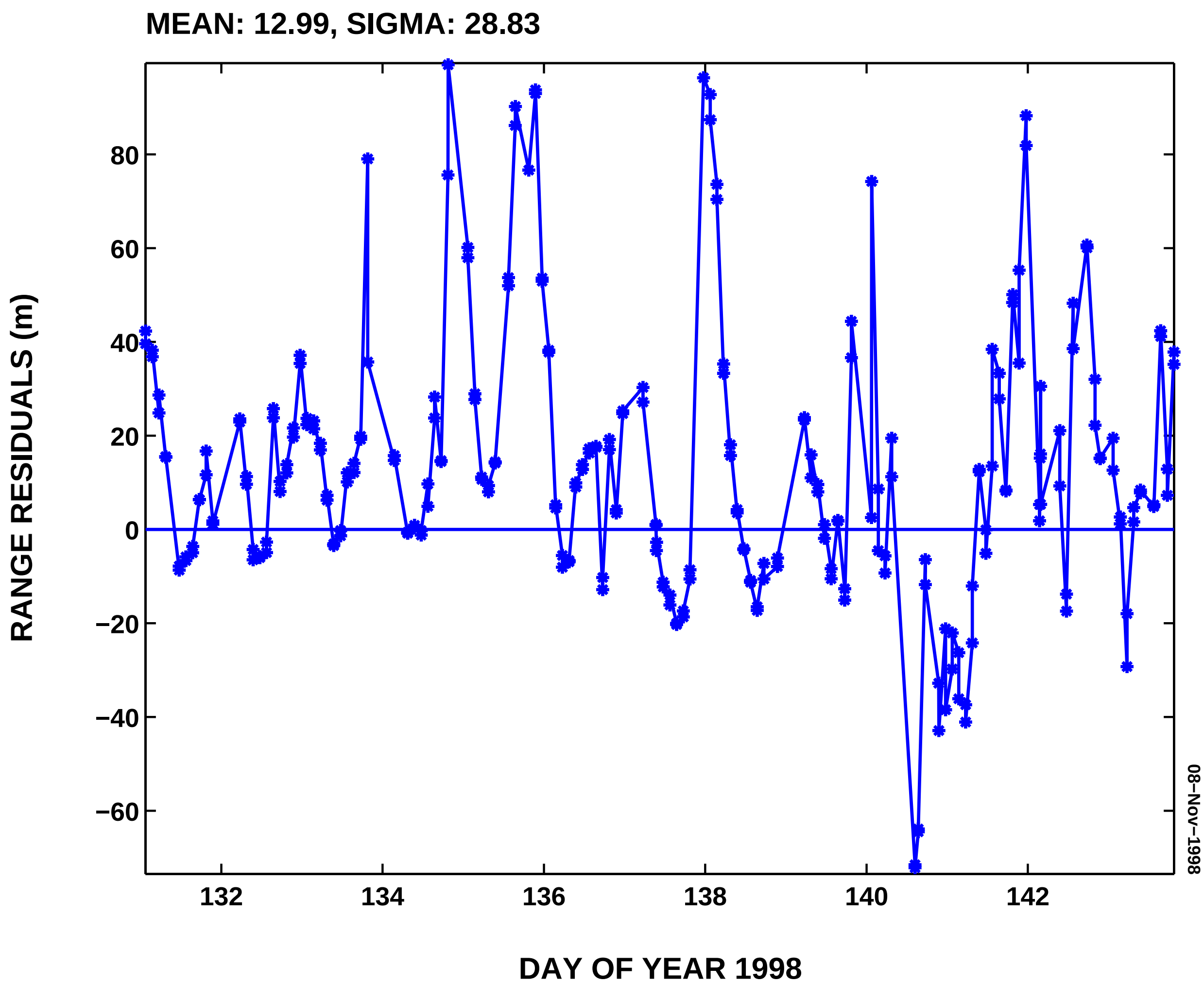


*Figure 3-25. Galaxy IV--Fillmore range residuals on Days 131-143 with bias removed.*

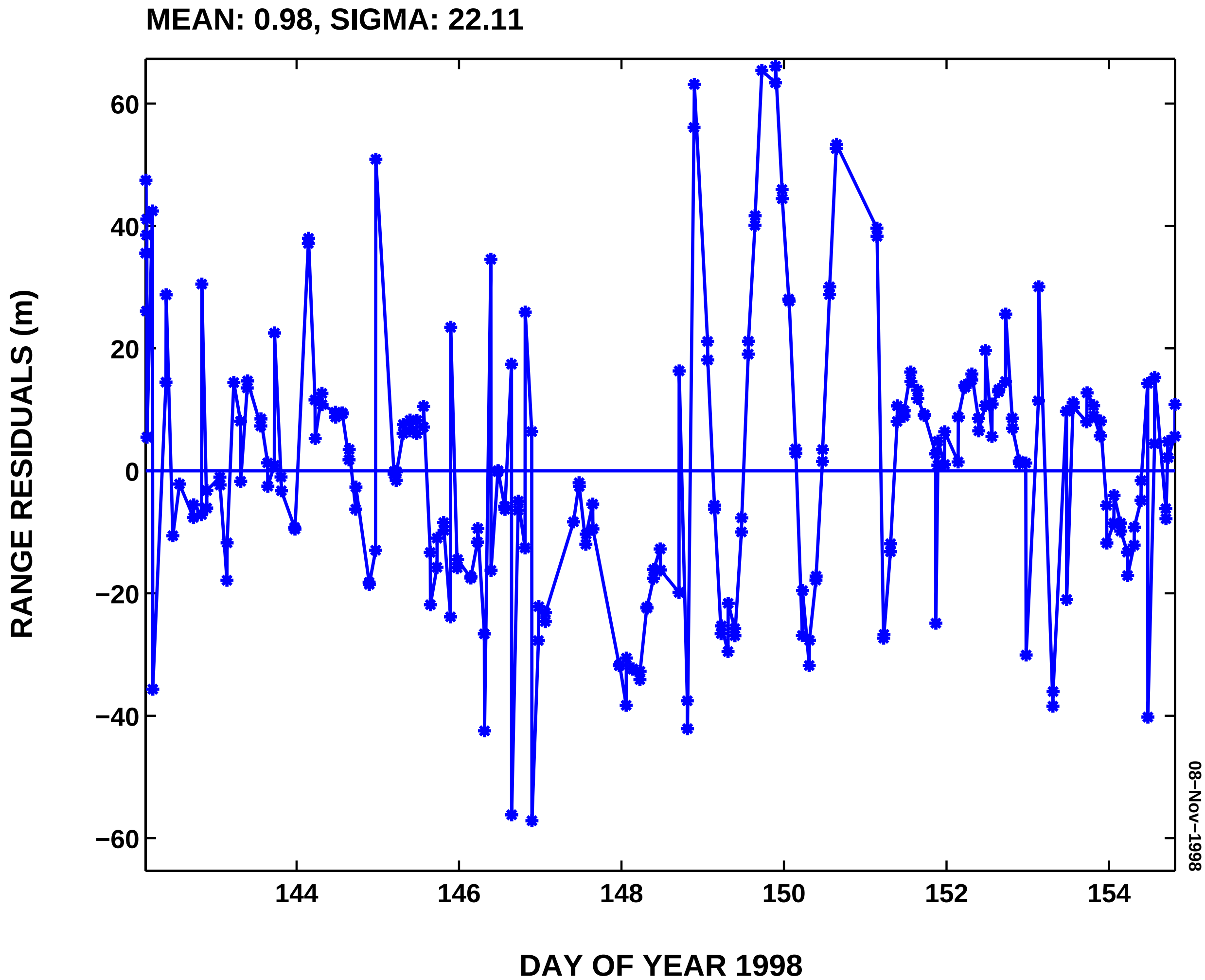


*Figure 3-26. Galaxy IV--Spring Creek range residuals on Days 142-154 with bias removed.*

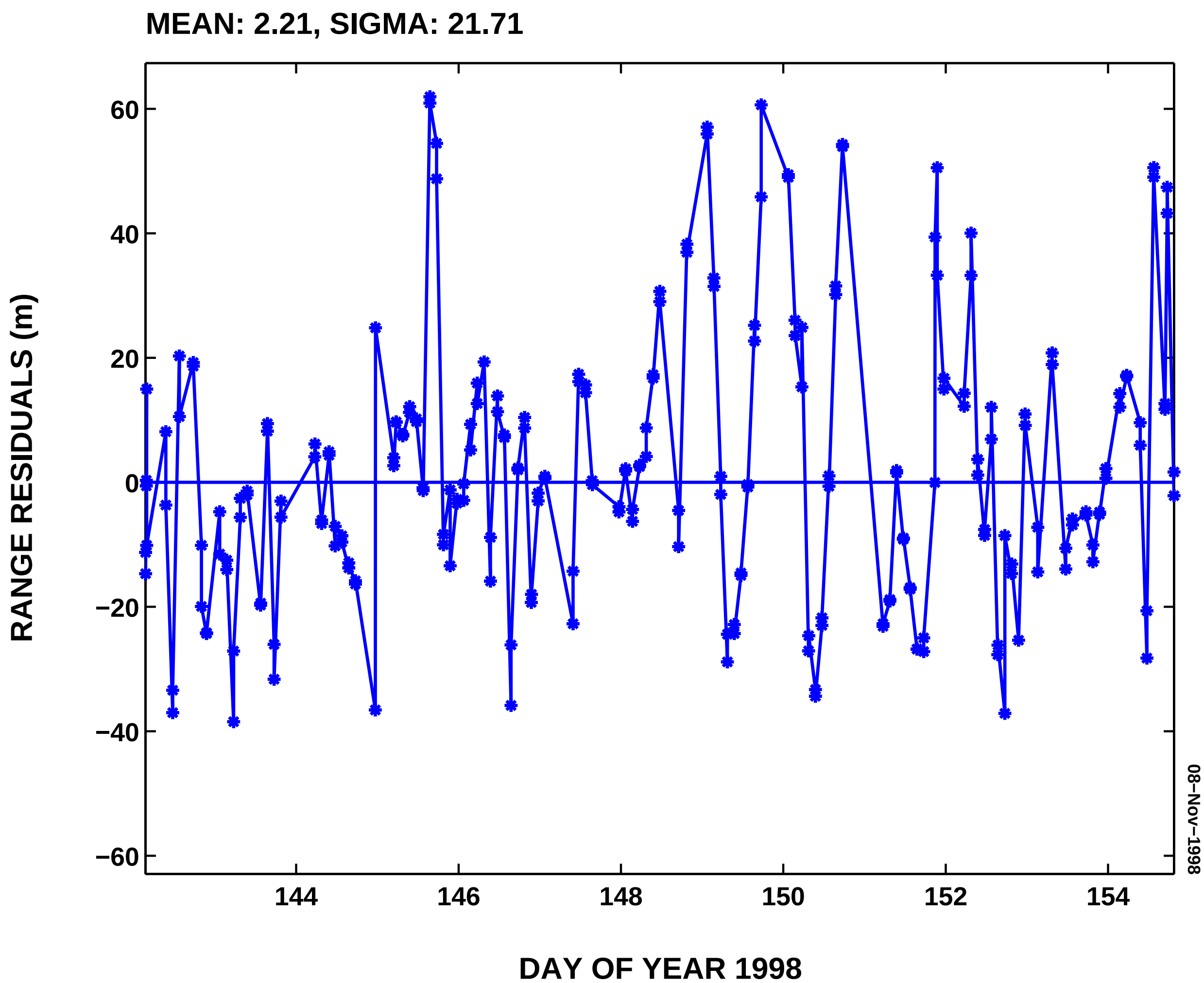


*Figure 3-27. Galaxy IV--Fillmore range residuals on Days 142-154 with bias removed.*

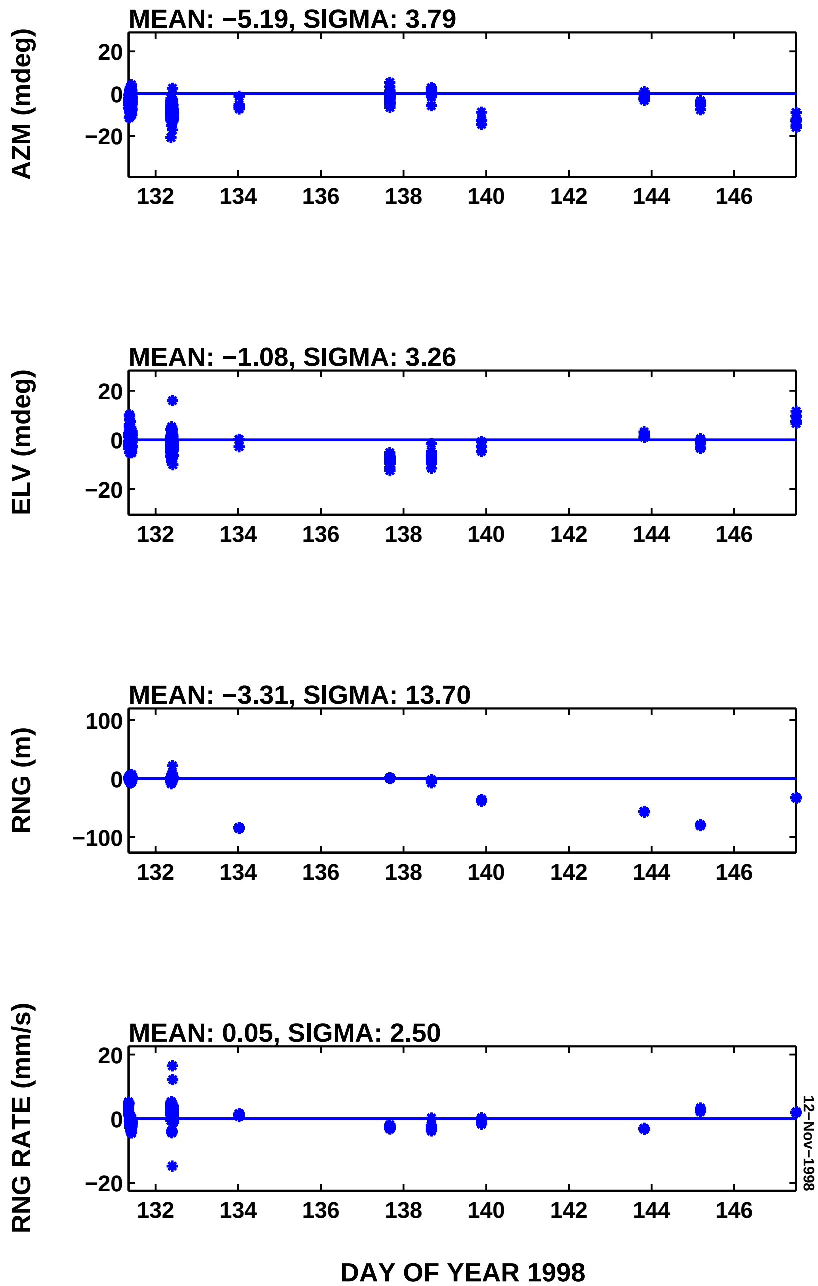


*Figure 3-28. Millstone measurement residuals for Galaxy IV on Days 131-147 with PanAmSat range data in orbit fit.*

## 3.5 EXAMPLE 5: PANAMSAT, GALAXY VI, SEPTEMBER 1998

This is a short example to check the calibration of PanAmSat using their range data with dense Millstone data.

Millstone took 16 tracks of Galaxy VI during Days 268 to 281 of 1998 in order to support a close encounter with Cosmos 2282. PanAmSat provided range data and maneuver information over that period. Galaxy VI maneuvered four times. The three thrust components were fit for each maneuver.

The PanAmSat data were weighted with a 16 m error. There were generally two PanAmSat measurements every one to two hours. The orbit fit span was over Days 268-281. A bias of -24 m was determined at Spring Creek, NY, and one of -34 m at Fillmore, CA. PanAmSat has adopted the biases to be -46 m and -85 m at Spring Creek and Fillmore, respectively. The plots of the PanAmSat residuals are shown in Figures 3-29 and 3-30 for Spring Creek and Fillmore, respectively. It is noted that the uncertainty of the bias estimates is on the order of 20-30 m. Part of this uncertainty is due to the inherent 16 m measurement error of the data as well as mismodeling of the four maneuvers. It is also noted that the Spring Creek, NY, bias uncertainty is smaller than for Fillmore, CA, as also seen in Figures 3-22 and 3-23. This may be due to coordinate error at Fillmore. Or it may be that Millstone and Spring Creek are relatively close together compared to Fillmore and that they are shaping the orbit and causing larger residuals for the Fillmore station. More data would be useful to see if the uncertainty of the range biases can be improved. The Millstone residuals are shown in Figure 3-31. Again, it is difficult to know if the -8 mdeg azimuth bias is due to orbit error or is inherent in the measurement. Given just two weeks of data, the number of maneuvers, and the noise of the data, this calibration effort seems quite good. Although, agreement of biases with PanAmSat was not as good as in the previous example.

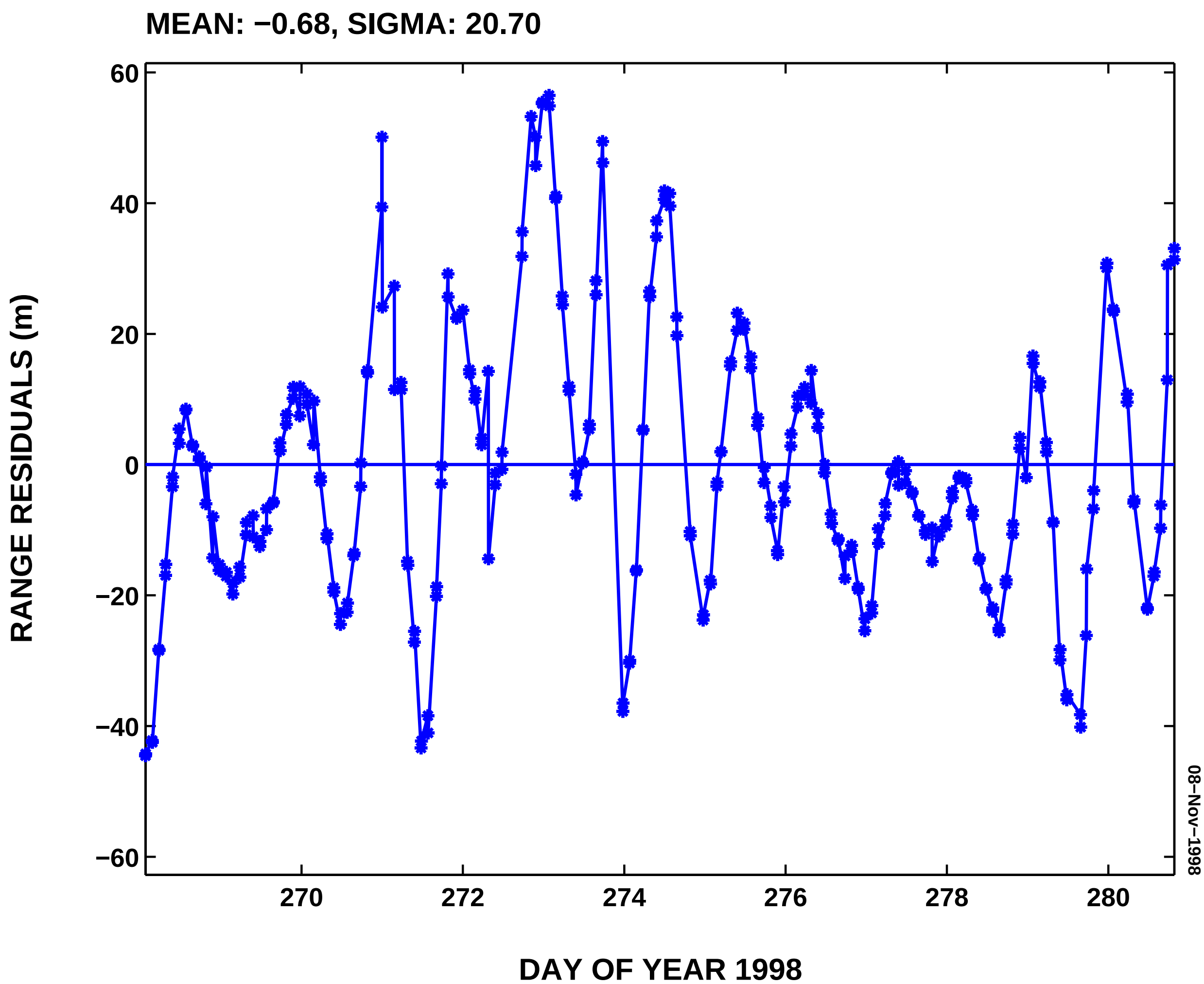


*Figure 3-29. Galaxy VI--Spring Creek range residuals on Days 268-280 with bias removed.*

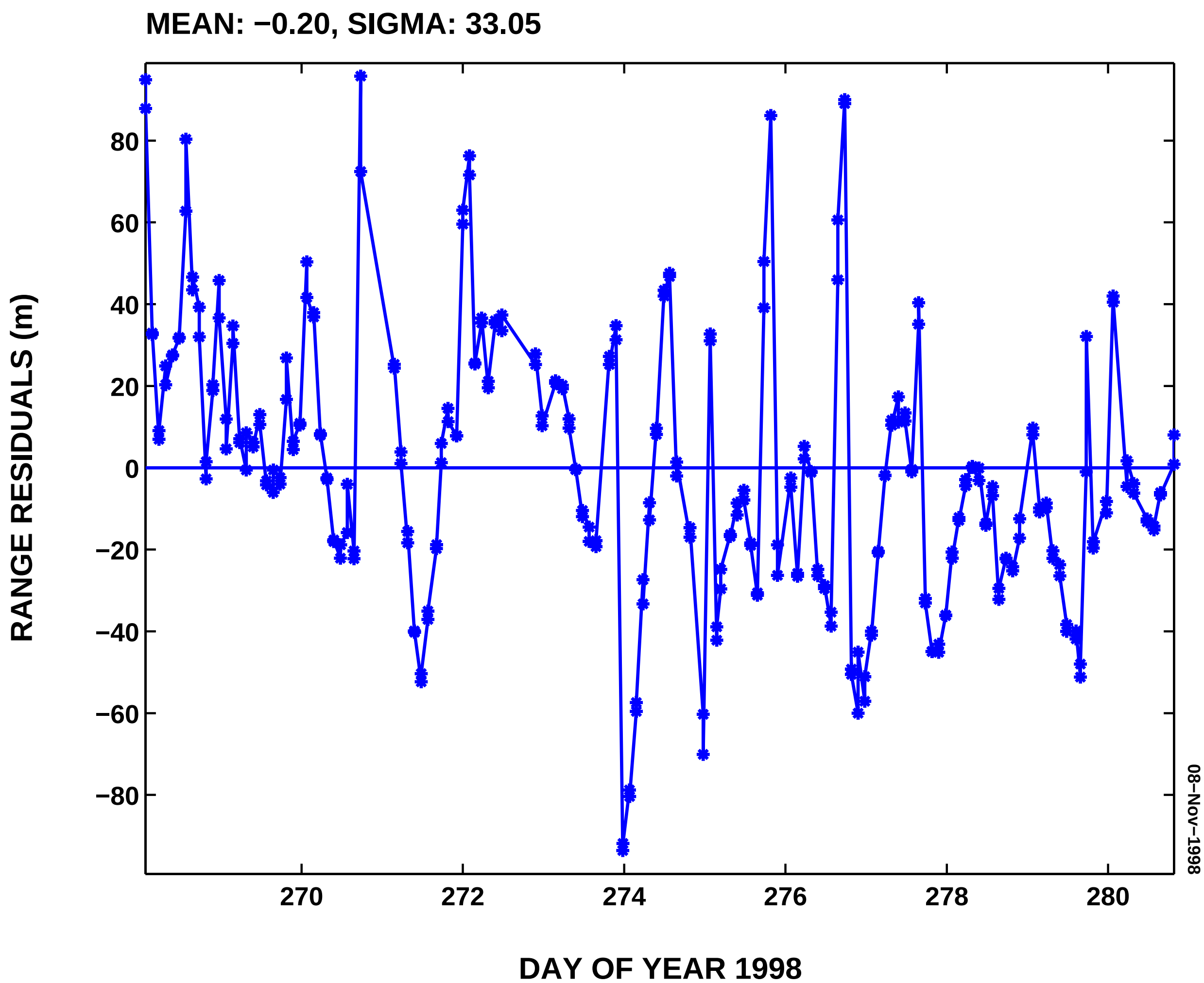


*Figure 3-30. Galaxy VI--Fillmore range residuals on Days 268-280 with bias removed.*

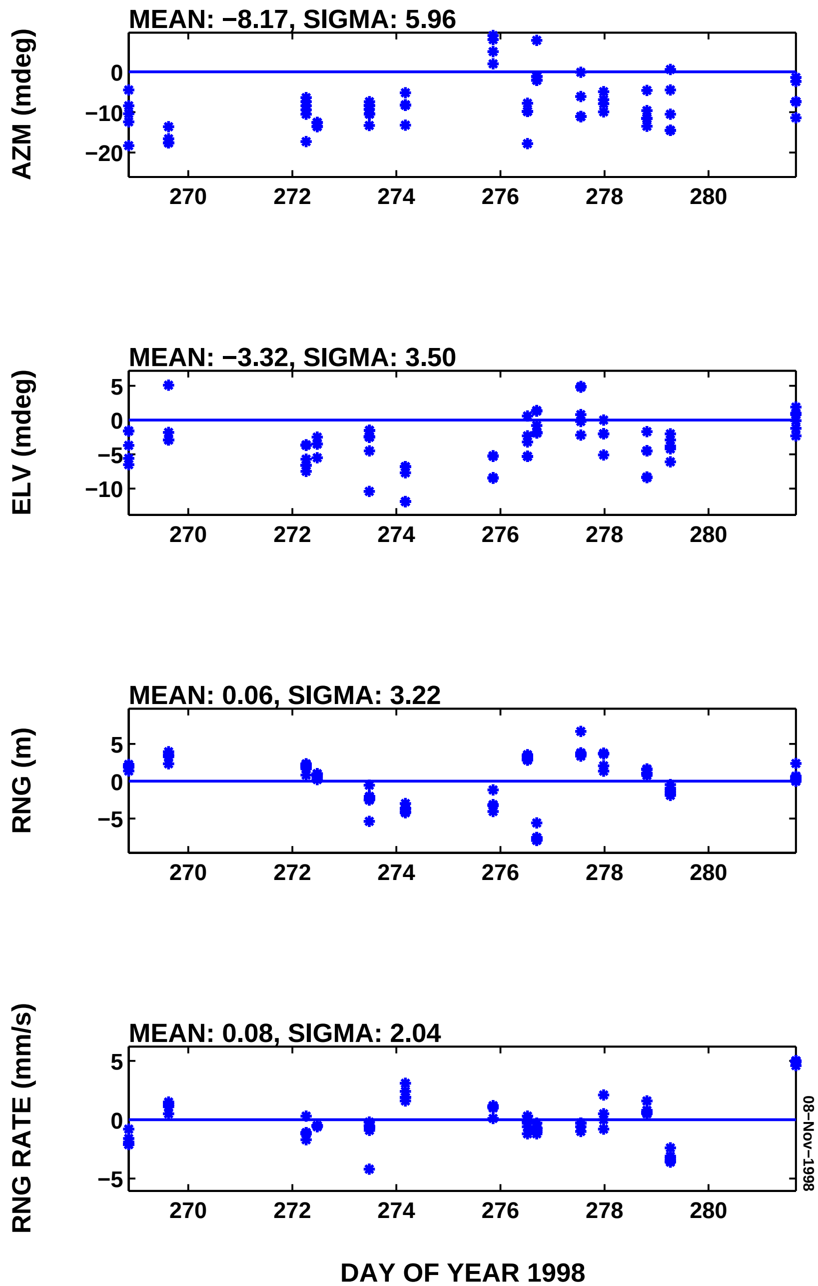


*Figure 3-31. Millstone measurement residuals for Galaxy VI on Days 268-281 with PanAmSat range data in orbit fit.*

## 3.6 EXAMPLES FROM THE OPERATIONAL MAINTENANCE OF CALIBRATION

In this section examples are shown of the operational calibration maintenance of CRDA satellites for which there has been regular receipt of CRDA range data: Anik E1 (Telesat Canada) discussed in more detail from Example 2, Anik E2 (Telesat Canada), Solidaridad 1 (SatMex), and Solidaridad 2 (SatMex). (Telesat Canada is also sending data for MSAT M01. The calibration for MSAT M01 is being examined and maintained, but will not be discussed here.) The Telesat and SatMex data are received routinely and pre-processed automatically as discussed above. The calibration of the data is reviewed and a table of range biases for each station-satellite combination is maintained. This table can then be accessed to calibrate the range data that are then available for encounter support.

The following Table 3-5 shows the start days of the current period of data, which have been calibrated on an operational basis. Periods of Millstone data that are relevant to the examples presented here are also shown with the number of tracks in parenthesis.

**TABLE 3-5**

**Current Period of Data Calibrated on an Operational Basis**

| | Begin Day | Millstone Tracking |
|---|---|---|
| Anik E1 (Telesat Canada) | 190/1998 | 203-228 (42), 234-259 (2) |
| Anik E2 (Telesat Canada) | 190/1998 | 203-233 (23), 234-259 (2) |
| Solidaridad 1 (SatMex) | 086/1998 | 243-270 (41) |
| Solidaridad 2 (SatMex) | 070/1998 | (0) relevant here |

The maneuver information is required for this operational approach; otherwise it would not be possible to maintain long orbit arc solutions (two weeks or more), which is what is required for this operational calibration. This information has been supplied routinely by Telesat Canada and SatMex.

Figures 3-11 and 3-12 of Example 2 (Section 3-2) show the initial calibration of Anik E1 data that have been obtained operationally. This calibration was with the period of dense Millstone data. Figures 3-32 and 3-33 show residuals for Allan Park and Edmonton respectively, from a fit over Days 234-259 (modeling through four maneuvers) when there were just two tracks of Millstone data. The range residuals are noisier either because the maneuvers could not be fit as well or because of other dynamic mismodeling. This shows that the biases have not changed, but that the calibration could only determine the biases to 30-40 m or so when little Millstone data were available. A long arc of seven weeks from Days 203-252 (modeling through seven maneuvers) was also examined. The residuals from this analysis are shown in Figures 3-34 and 3-35 for Allan Park and Edmonton, respectively. The residuals were less noisy during the early part of the 48-day span (Days 203-228--modeling through four maneuvers) when Millstone data were available to help fit through the maneuvers. The biases again are stable and the uncertainties reduced with the larger sample of data. (Structure with roughly a two-week period is seen, again the exact cause could be maneuver or other dynamic mismodeling, e.g., radiation pressure.) This last example shows the possible recourse to even longer arcs to examine the calibration.

A similar analysis was performed for Anik E2. Anik E2 is a bit difficult to model dynamically since it has roughly 50 small thrusts per day to maintain attitude control. One approach has been to solve for an along track acceleration term to absorb the effect of these thrusts. Consistent values for this term have been obtained for orbit fits over the Day 203-259 period (modeling through ten maneuvers) and it dramatically improves the overlap quality, as well as has a noticeable improvement on the range residuals. This approach seems to help more when there are not dense Millstone data to help determine the maneuvers. There were about half as much Millstone data available as for Anik E1 during the Days 203-232 period (modeling through seven maneuvers). A fit over this span was performed to establish a calibration. Figures 3-36 and 3-37 show the residuals for Allan Park and Edmonton, respectively. Biases were determined with uncertainties on the order of 11 m. A fit over the Day 234-259 period (modeling through three maneuvers) shows the calibration with little Millstone data (two tracks), and the residuals for Allan Park and Edmonton for this fit are shown in Figures 3-38 and 3-39, respectively. The uncertainties in the biases have grown to about 25 m although their values have not changed much. Using less Millstone data, introduces larger uncertainties in the bias estimates.

For the three orbit periods discussed here for Anik E1 and Anik E2, overlaps to indicate orbit quality as shown in Table 3-6. For Anik E2 over Days 203-232, with modest Millstone tracking, the orbit quality is at the 150-m level. With less Millstone tracking (two tracks), but using the established biases for calibration of the Anik E1 and Anik E2 data, the orbit quality for both satellites over the Days 234-259 period is at the 0.5 to 1 km level. The larger errors may be due to more difficulty solving for the thrust components when little Millstone data were available.

**TABLE 3-6**

**Summary of RMS Differences of Overlapped Orbits for Anik E1 and Anik E2 Using Telesat and Millstone Data**

| Satellite | Fit Span of Orbits Overlapped | Along Track (m) | Cross Track (m) | Radial |
|---|---|---|---|---|
| Anik E1 (2 tracks MH) | 234-246 vs. 246-259 | 221 | 867 | 113 |
| Anik E2 (23 tracks MH) | 203-219 vs. 219-232 | 155 | 37 | 10 |
| Anik E2 (2 tracks MH) | 234-246 vs. 246-259 | 217 | 355 | 100 |

The biases determined for Anik E1 and Anik E2 for Allan Park and Edmonton are shown in Table 3-7. For these maneuvering satellites, the calibration is dependent in part on the ability to fit the maneuvers as well as to understand what else may not be well modeled dynamically. The Millstone range data helps here by adding additional station geometry and the three other measurements at azimuth, elevation, and range rate. When dense Millstone data are available, the uncertainties are 10 m or better. With significant decrease in Millstone data (just a few tracks), the uncertainties become larger and are more typically 20-40 m.

**TABLE 3-7**

**Range Biases Determined for Station-Satellite Combinations**

| Satellite | Station | Bias (m) |
|---|---|---|
| Anik E1 | Allan Park | -84 |
| Anik E1 | Edmonton | 74 |
| Anik E2 | Allan Park | -26 |
| Anik E2 | Edmonton | 57 |
| Solidaridad 1 | Hermosillo A | 93 |
| Solidaridad 1 | Iztapalapa D | 68 |
| Solidaridad 2 | Hermosillo B | 68 |
| Solidaridad 2 | Iztapalapa B | 64 |
| Solidaridad 2 | Iztapalapa T-Tach | 80 |

The structure of the residuals seen in Figures 3-36 to 3-39, which have large scatter over periods of time, is caused by dynamic mismodeling, either of the thrusts or possibly radiation pressure. For this operational approach, only the maneuver times are requested of the CRDA partners and all three thrust components (along track, cross track, and radial) are solved for. Solving for just the primary thrust component did not work well in these cases for the Anik satellites.

SatMex has provided data for Solidaridad 1 from Day 086 to Day 250 of 1998 and for Solidaridad 2 from Day 070 to Day 249. For the example to be discussed here, Millstone tracked Solidaridad 1 densely (41 tracks) from Days 243-270 to support a Telstar 401 encounter. There were no Millstone tracks for Solidaridad 2 for the example to be discussed, and therefore just SSN data were used to compute the orbit. In this example, orbit fits were performed over Days 241-271 for both satellites to determine the biases. For Solidaridad 1, there were five maneuvers over this period and six for Solidaridad 2. These maneuvers were modeled by solving for the three thrust components of each maneuver during the orbit fit. Solving for just the primary component was not successful. This example will show calibration for both SatMex satellites and the orbit quality for Solidaridad 1 only with and without dense Millstone data.

The range residuals from the Solidaridad 1 fit are shown in Figures 3-40 and 3-41 for Hermosillo F and Iztapalapa D, respectively, for the orbit fit after the calibration was performed. The calibration was performed iteratively, and the data were assigned an error of 4 m. The Millstone residuals are shown in Figure 3-42 and are typical. The biases are shown in Table 3-7 and are determined with an uncertainty on the order of 4 m.

The range residuals from the Solidaridad 2 fit are shown in Figures 3-43 to 3-45 for Hermosillo B, Iztapalapa B, and Iztapalapa T-Tach, respectively. The residuals were larger at times due to difficulty fitting the maneuvers, which occurred on Days 244, 246, 247, 258, and 261. These biases were iterated to near zero, with uncertainties on the order of 20 m for Hermosillo B and Iztapalapa D which had four to five tracks and 40 m for Iztapalapa T-Tach, which had just one track. The bias determination for Iztapalapa T-Tach was probably also affected by the maneuver modeling error. For Hermosillo B and Iztapalapa D, with the three-sigma filter, a lot of data were being thrown out in a few tracks as there was difficulty fitting the six maneuvers to the level desired, and the data were quite noisy in those tracks. The three-sigma filter was throwing out more than a few outliers, and was not used in Figures 3-43 and 3-44.

It is interesting to compare the orbit quality for the two satellites over this period, one (Solidaridad 1) having a lot of Millstone data and the other (Solidaridad 2) not. To do this, two orbits were computed for each satellite, over Days 241-256 and Days 256-271 giving one day of overlap for these 16 day fits. The overlap comparison is shown in Table 3-8.

**TABLE 3-8**

**Summary of RMS Difference of Overlapped Orbits on Day 256 Using SatMex and Millstone Data**

| | Along Track (m) | Cross Track (m) | Radial (m) |
|---|---|---|---|
| Solidaridad 1 (41 tracks MH) | 67 | 112 | 13 |
| Solidaridad 2 (No MH) | 444 | 97 | 145 |
| Solidaridad 1 (No MH) | 277 | 158 | 16 |
| Solidaridad 1 (MH only) | 814 | 3691 | 411 |

The first line of Table 3-8 shows the overlap for Solidaridad 1 when the 41 tracks of Millstone data were used to help calibrate the SatMex data and to compute the orbits. As there were no Millstone data for Solidaridad 2 over this period, the second line of the table shows the overlap with just the SatMex data and as calibrated using range biases from Table 3-7. And the third line shows how well Solidaridad 1 performed once it was calibrated, but without Millstone in the final orbit determination. Maneuver modeling error probably made the results of lines two and three larger than expected. With the calibration from Table 3-7, the RSS sum of the differences of the overlaps of the orbits determined with just calibrated SatMex data is 300-500 m (remember this is the sum of the error of both overlapped orbits). With Millstone data included in the orbit fit for Solidaridad 1, the total overlap RSS difference is 130 m. Finally, line 4 of Table 3-8 shows the overlap of the Solidaridad 1 orbits computed with just the Millstone data. These differences are typical, showing the largest error in cross track and using one half of the overlap difference as the error yields the usual 2 km error for each overlapped orbit.

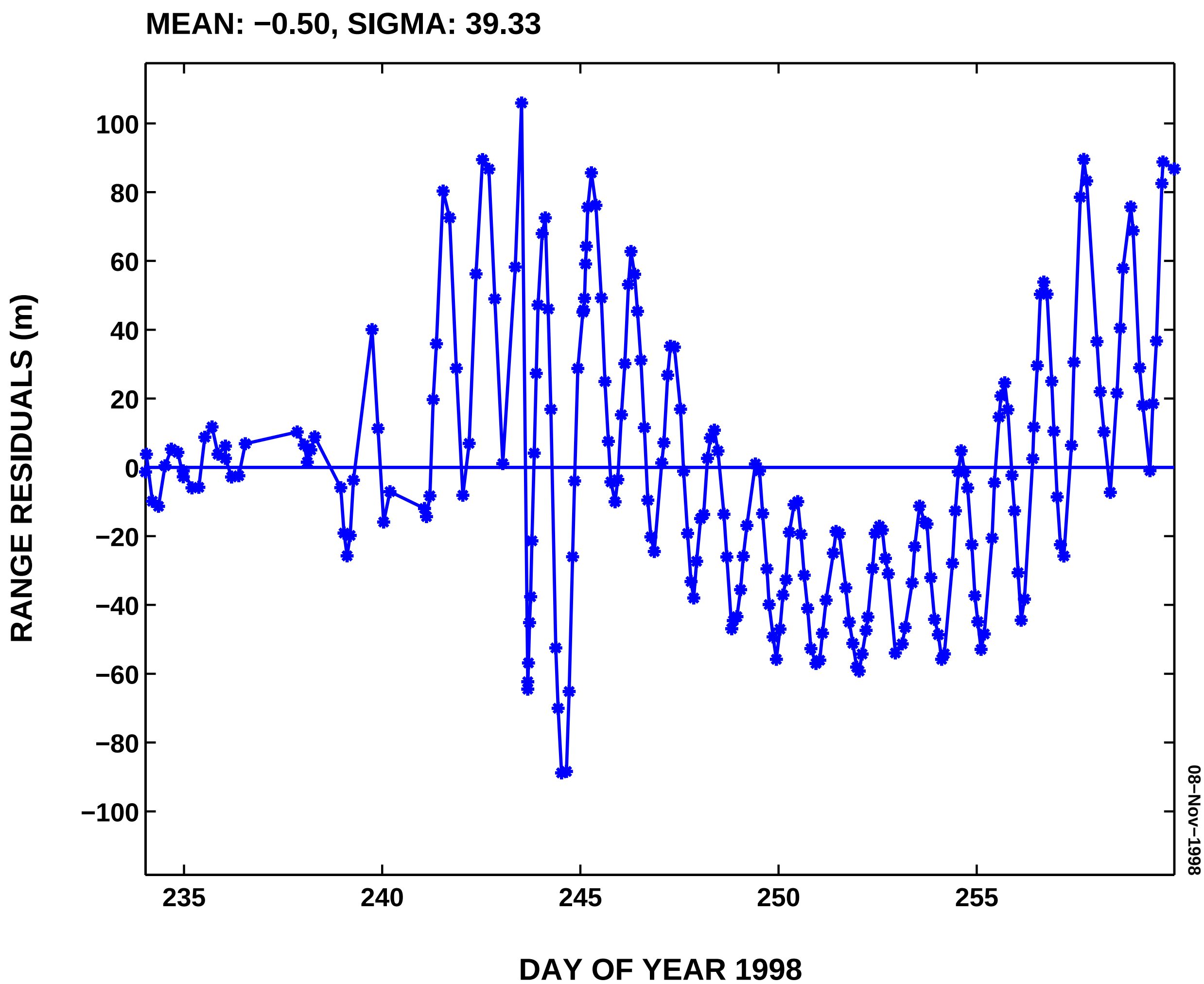


*Figure 3-32. Allan Park--Anik E1 residuals on Days 234-259 with bias removed.*

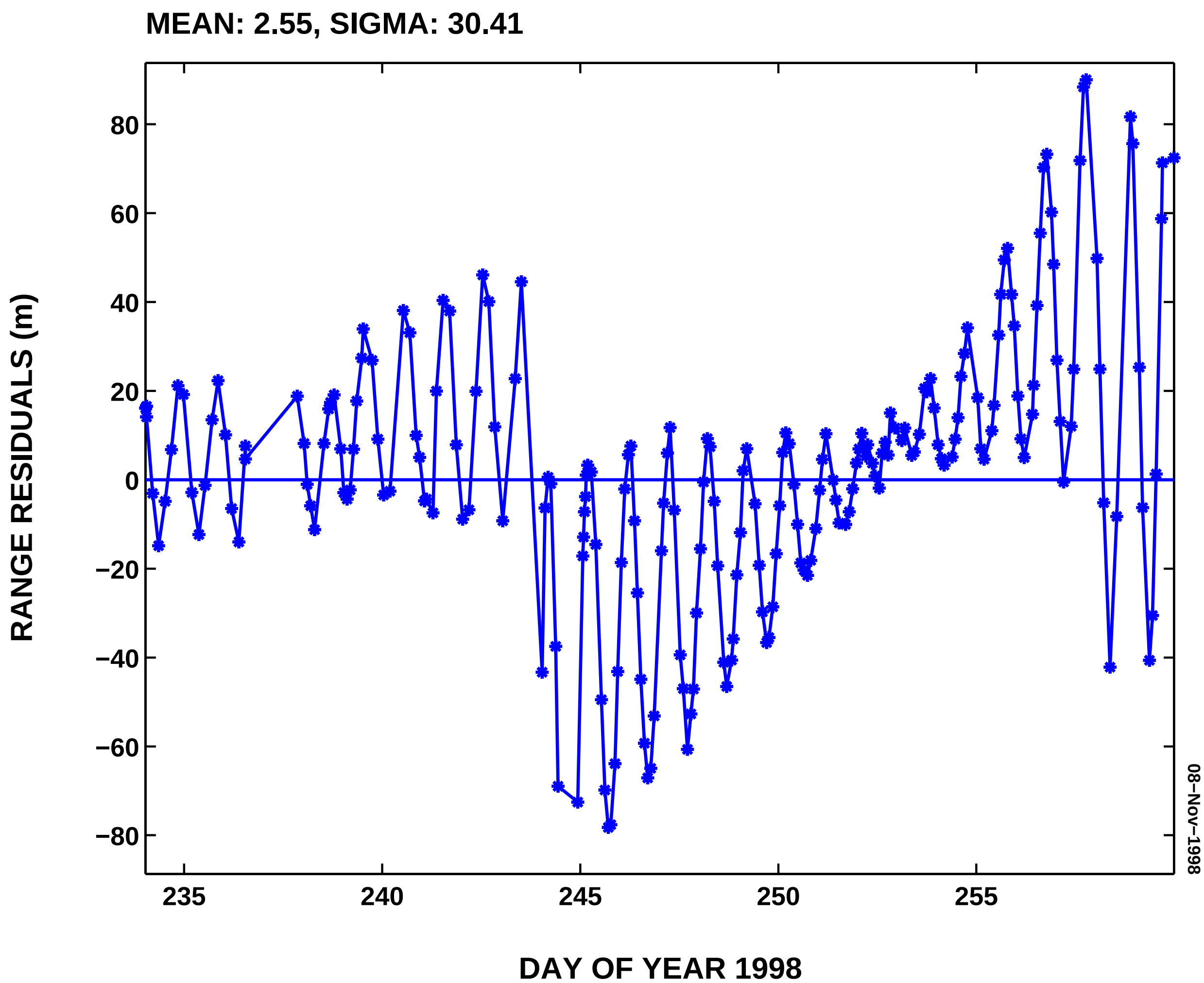


*Figure 3-33. Edmonton--Anik E1 residuals on Days 234-259 with bias removed.*

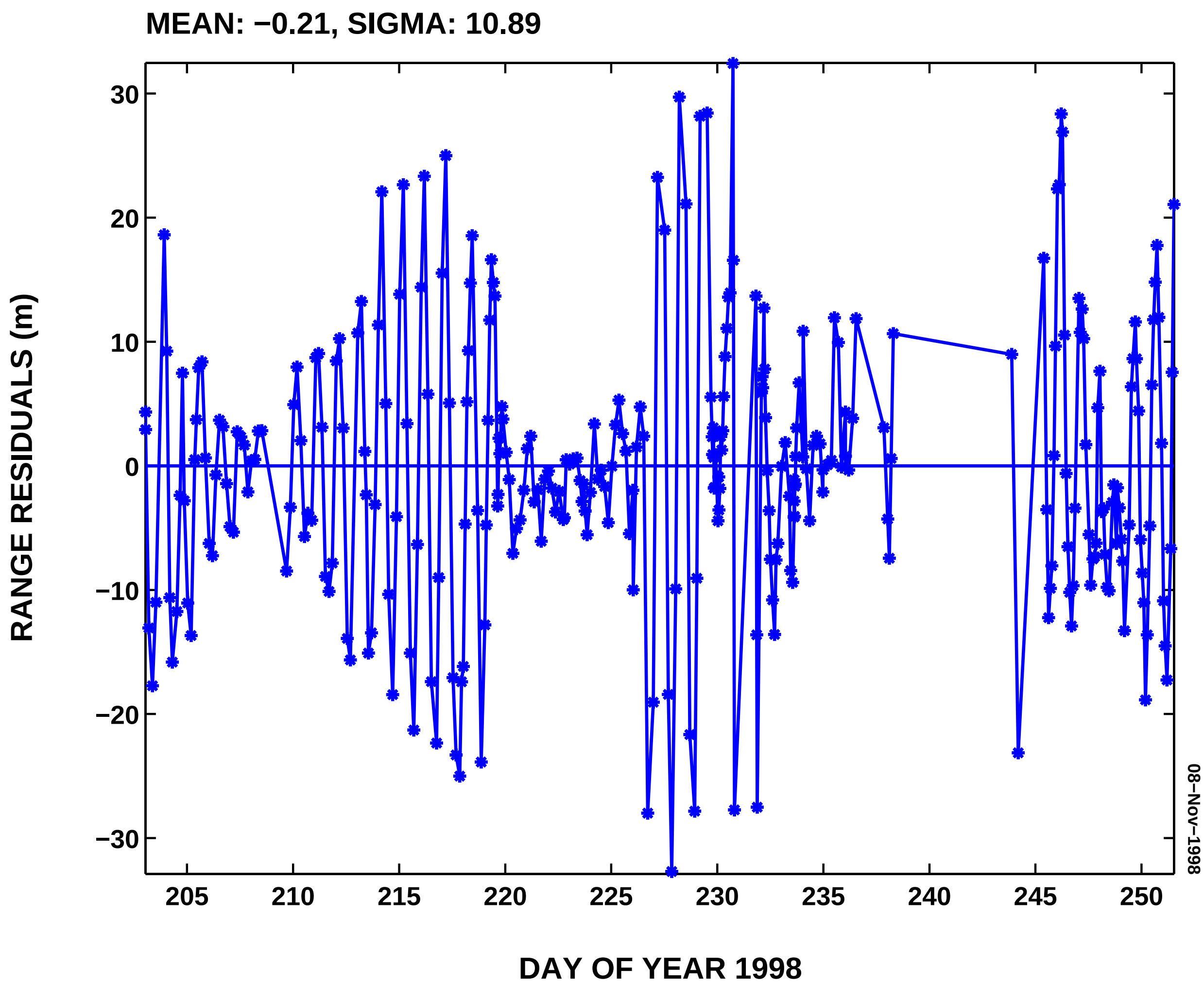


*Figure 3-34. Allan Park--Anik E1 residuals on Days 203-251 with bias removed.*

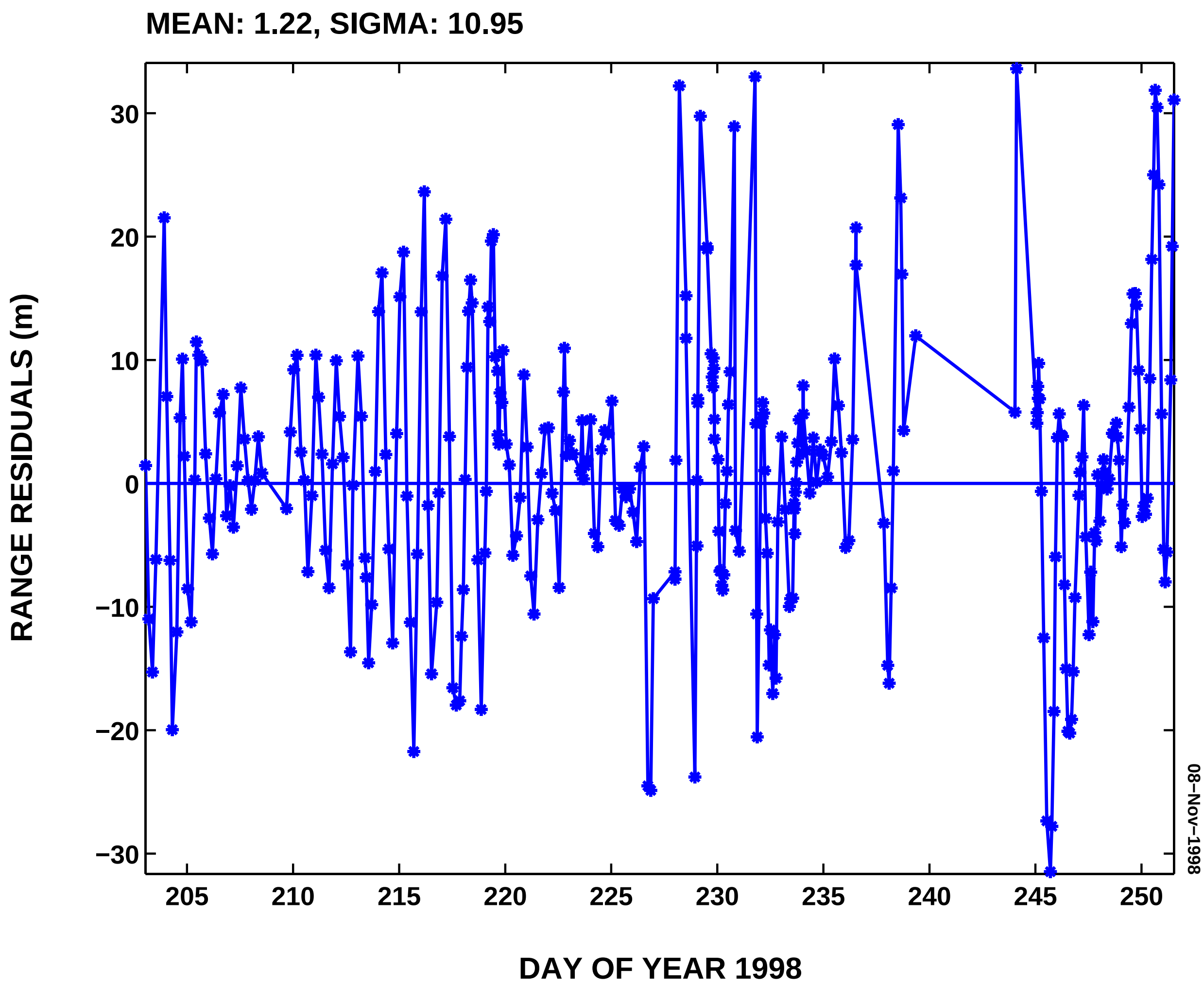


*Figure 3-35. Edmonton--Anik E1 residuals on Days 203-251 with bias removed.*

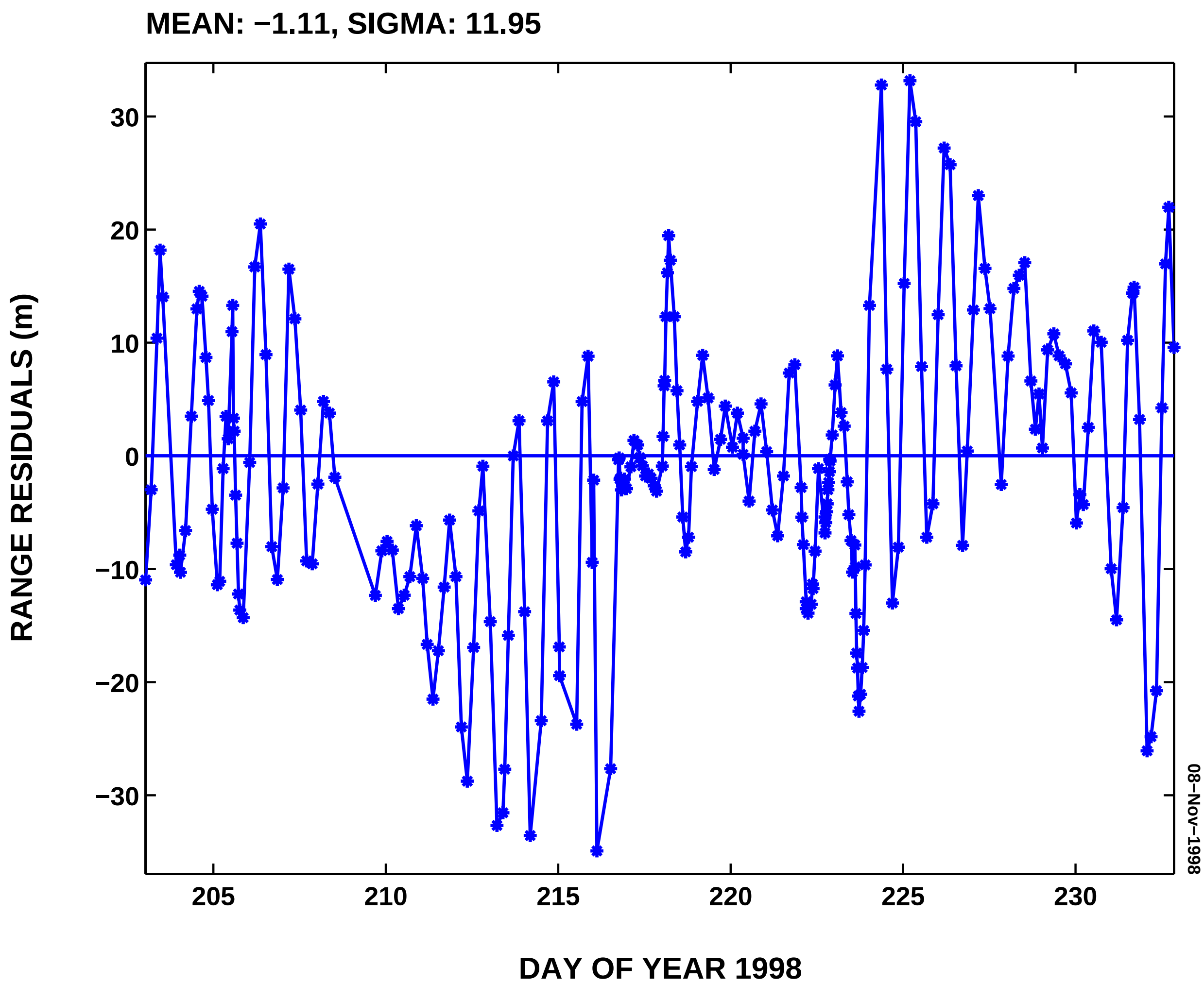


*Figure 3-36. Allan Park--Anik E2 residuals on Days 203-232 with bias removed.*

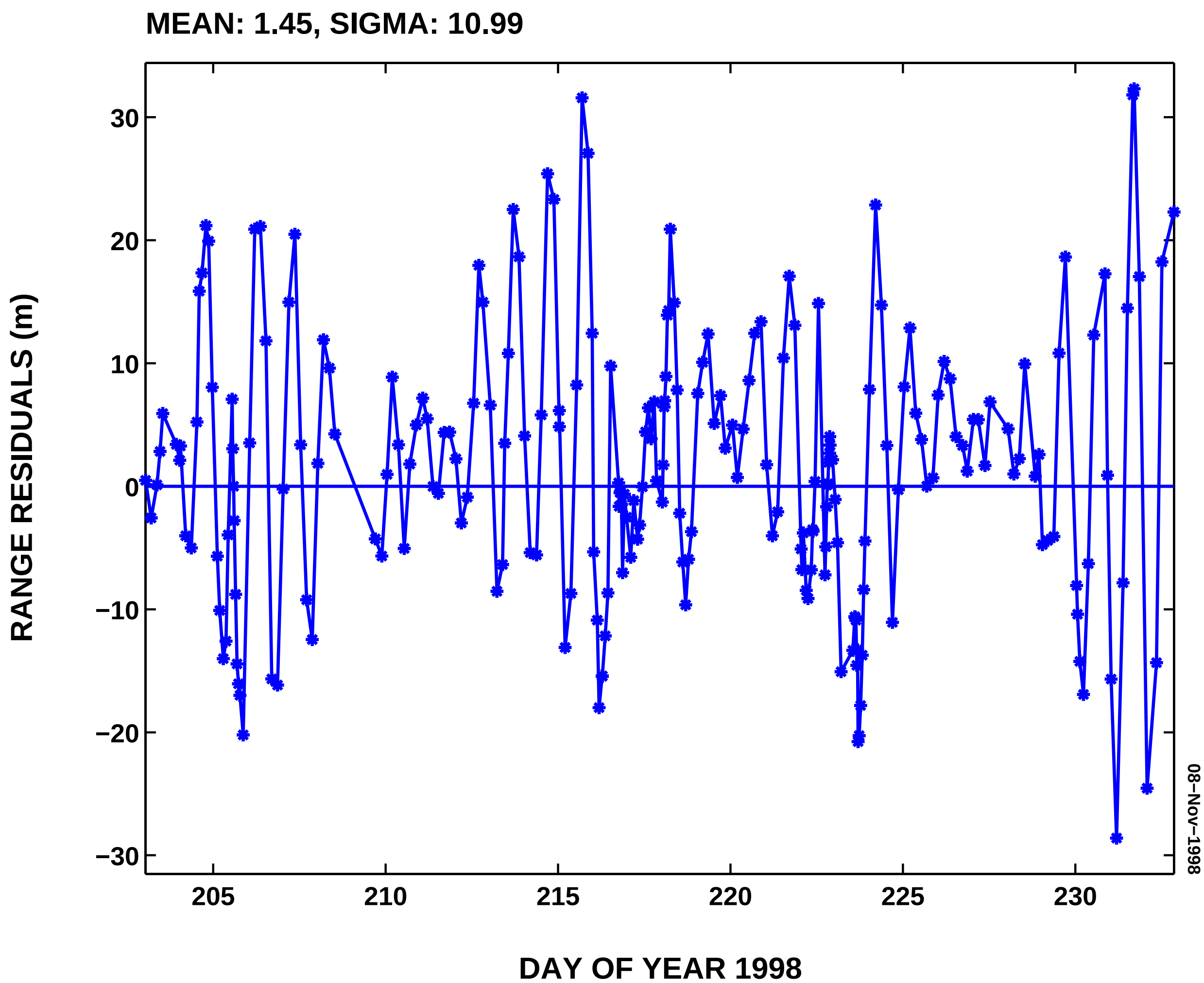


*Figure 3-37. Edmonton--Anik E2 residuals on Days 203-232 with bias removed.*

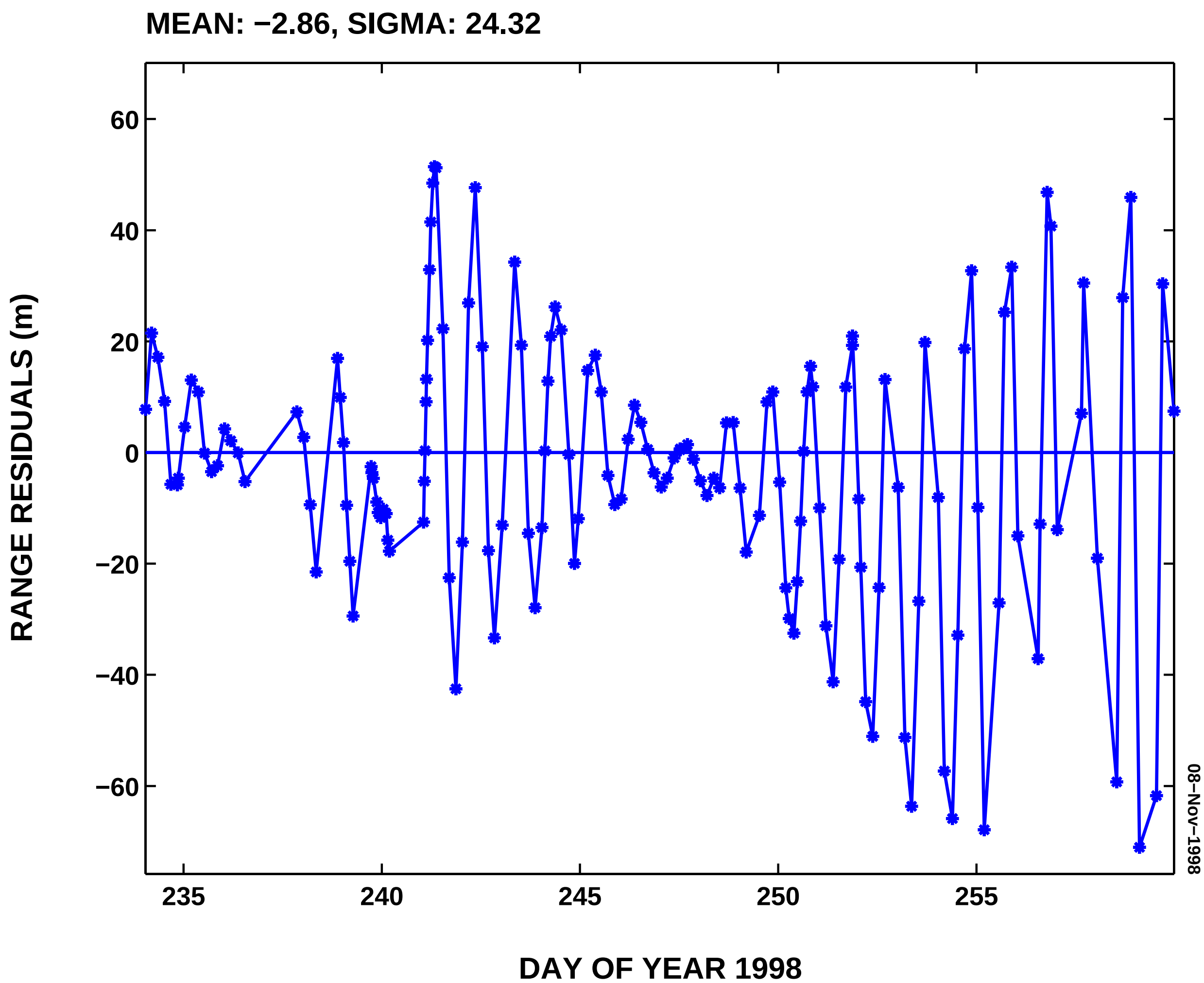


*Figure 3-38. Allan Park--Anik E2 residuals on Days 234-259 with bias removed.*

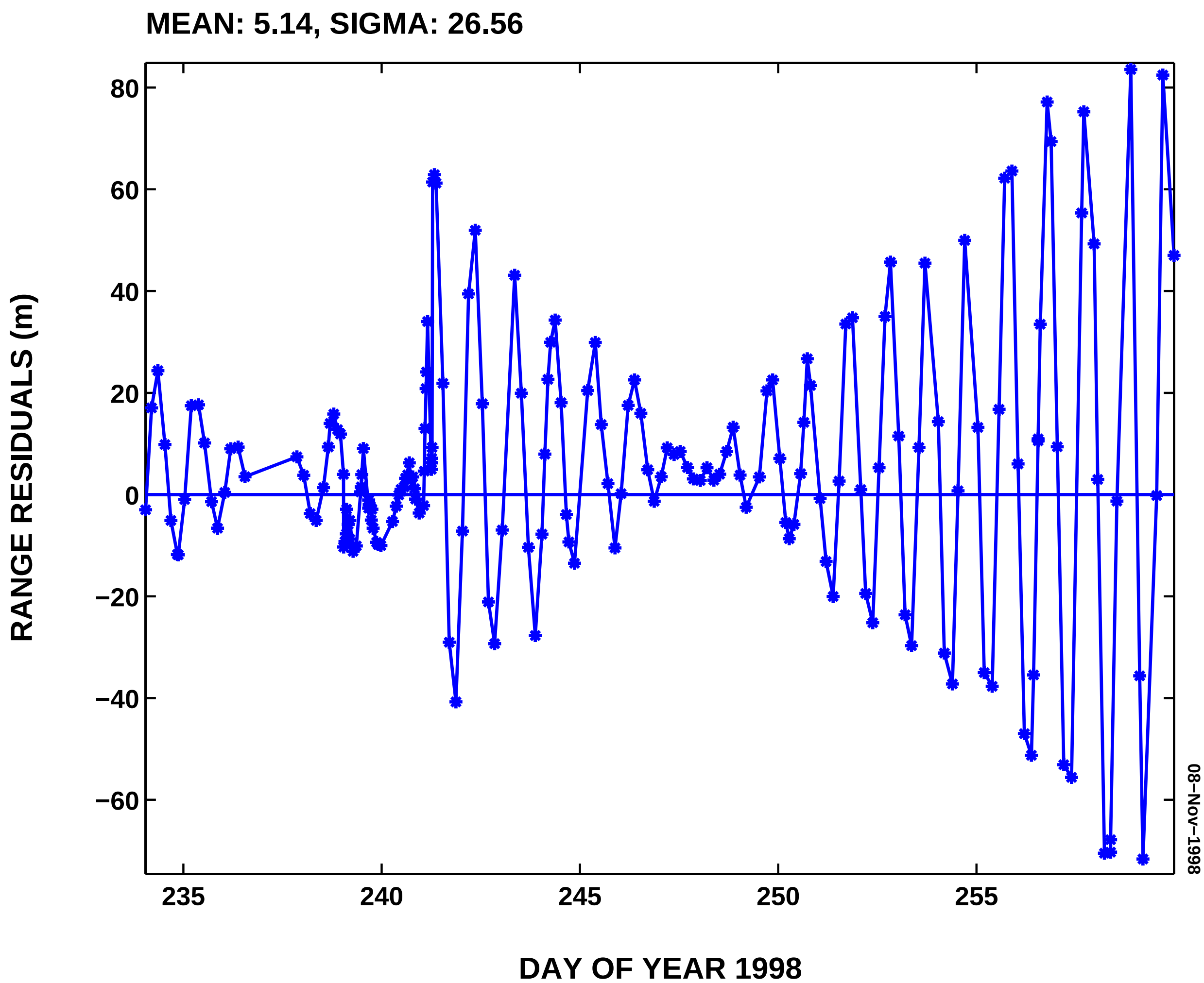


*Figure 3-39. Edmonton--Anik E2 residuals on Days 234-259 with bias removed.*

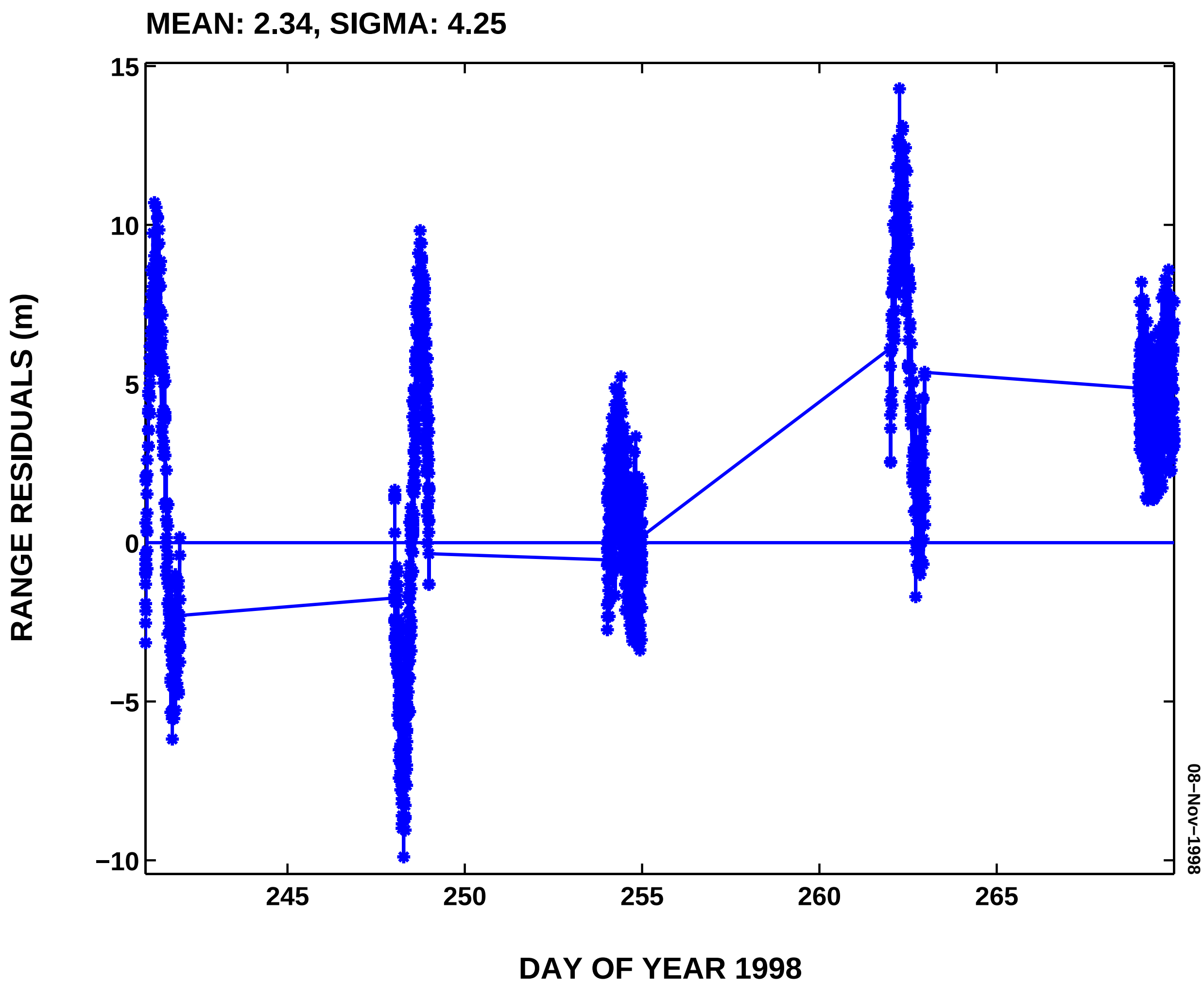


*Figure 3-40. Hermosillo A--Solidaridad 1 range residuals through Days 241-269 with bias removed.*

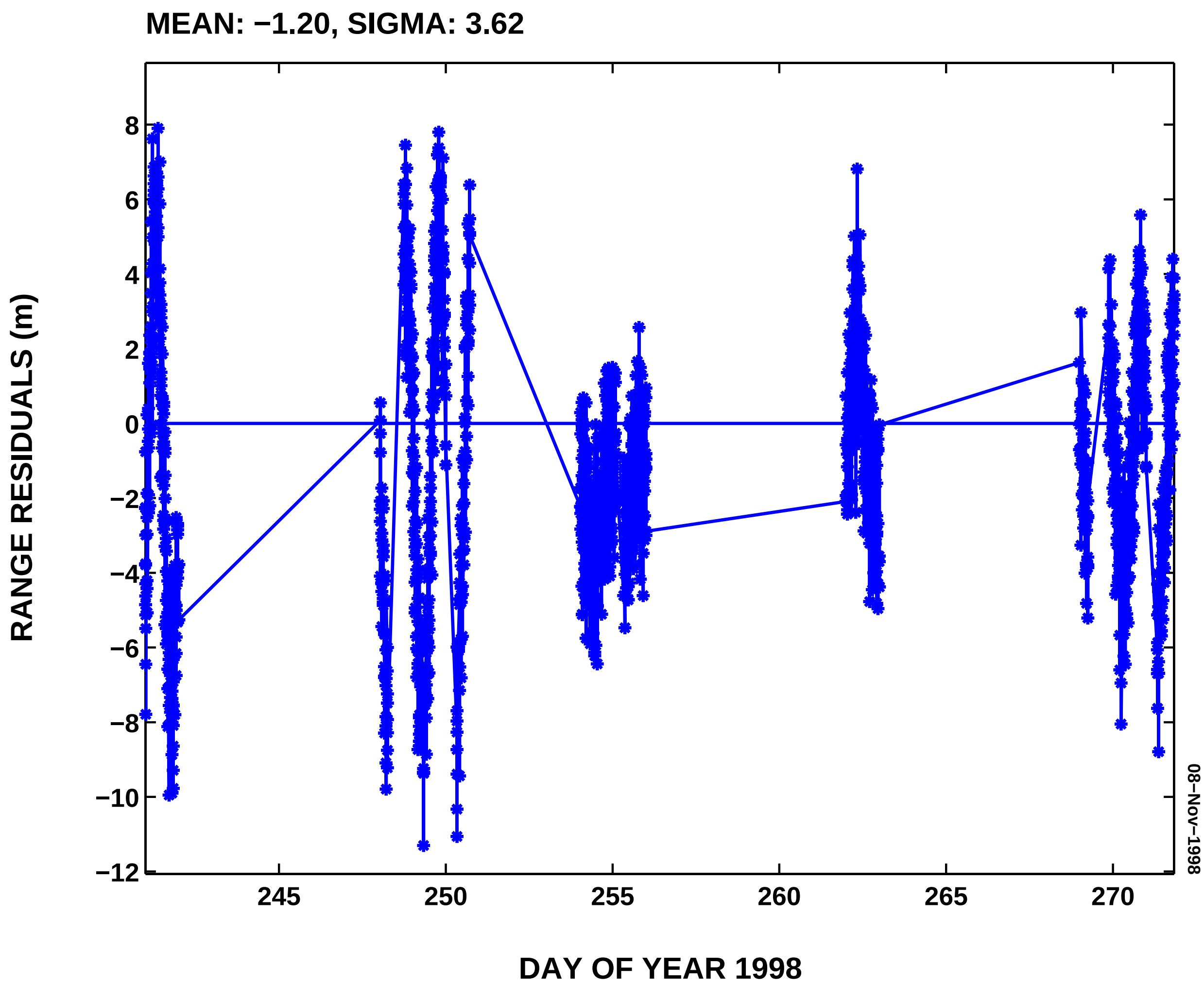


*Figure 3-41. Iztapalapa D--Solidaridad 1 range residuals through Days 241-271 with bias removed.*

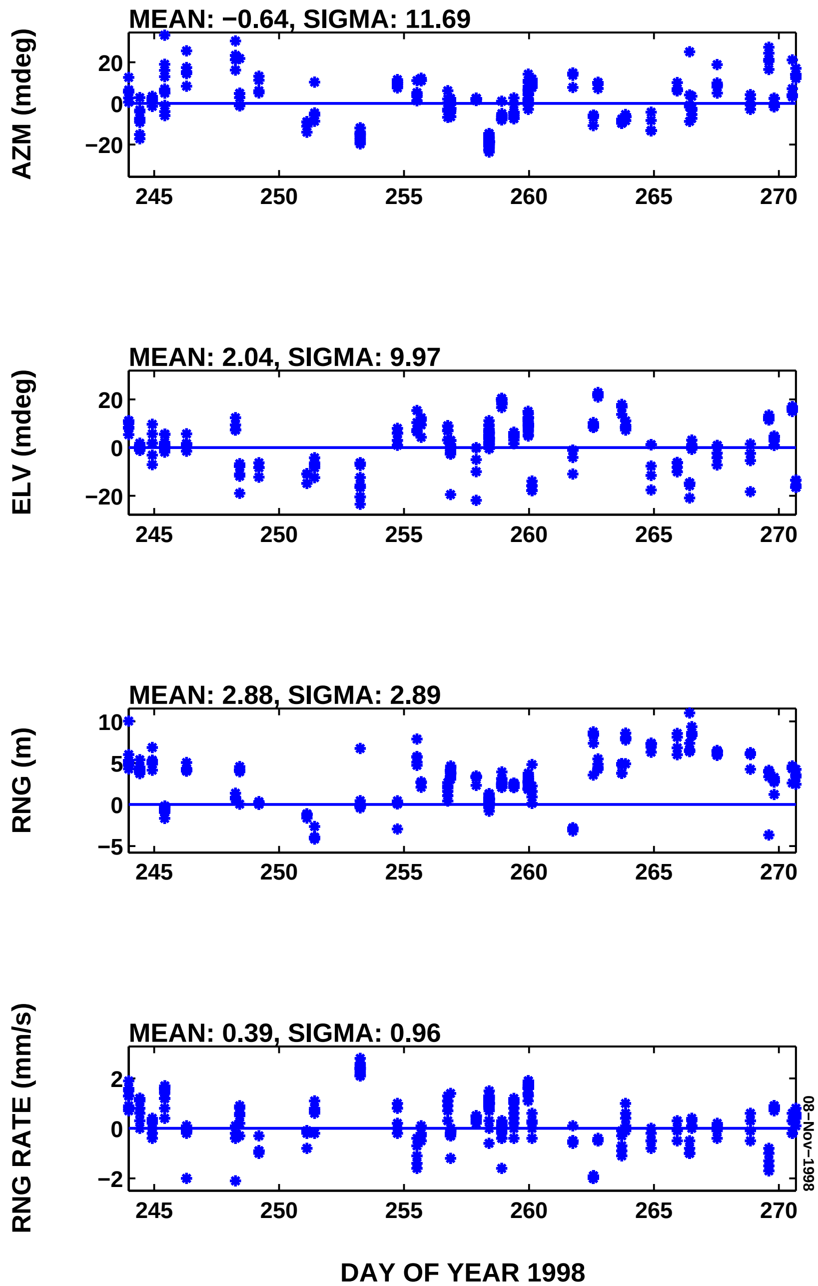


*Figure 3-42. Millstone measurement residuals for Solidaridad 1 on Days 244-270 with SatMex range data in orbit fit.*

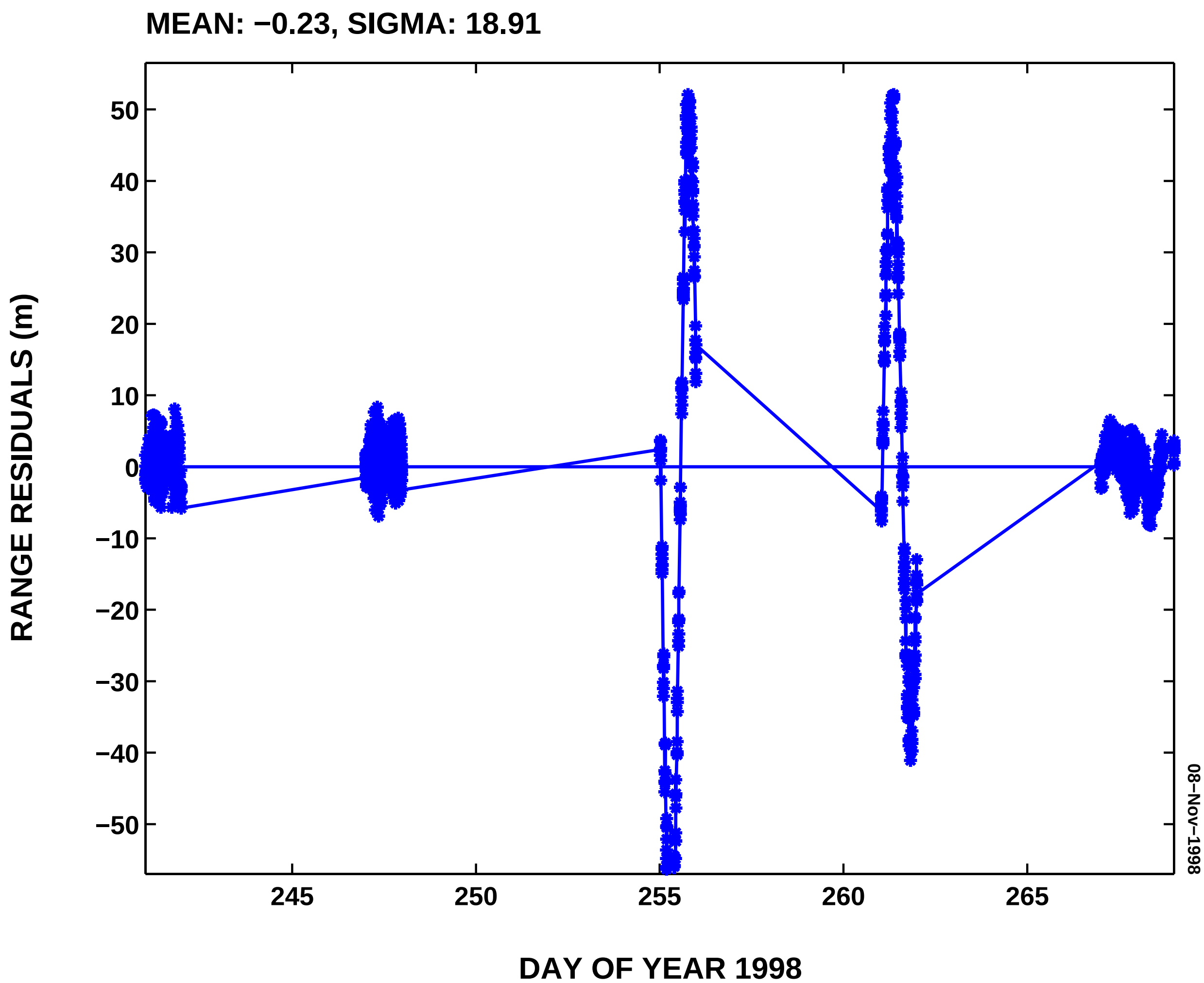


*Figure 3-43. Hermosillo B--Solidaridad 2 range residuals through Days 241-268 with bias removed.*

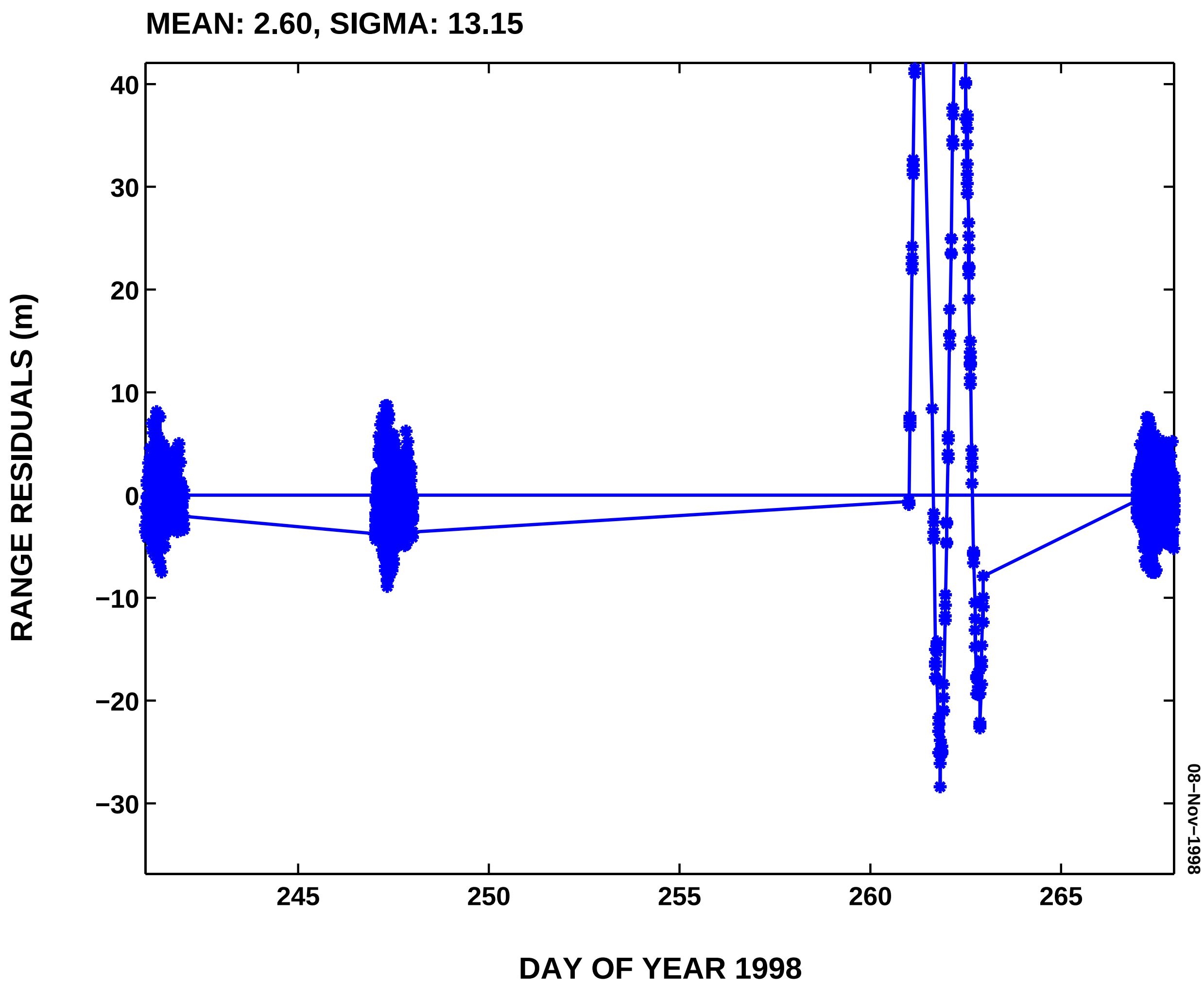


*Figure 3-44. Iztapalapa D--Solidaridad 2 range residuals through Days 241-267 with bias removed.*

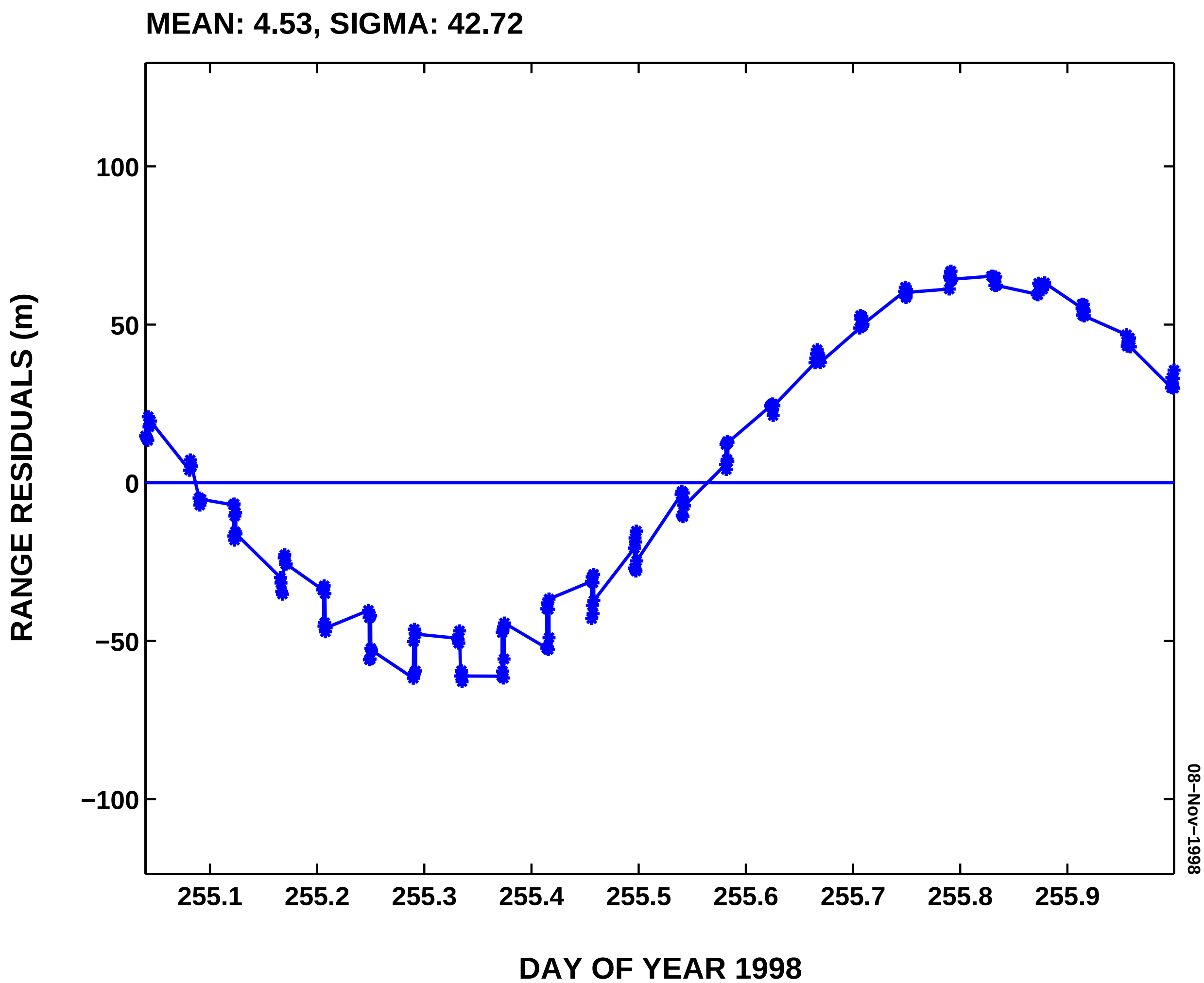


*Figure 3-45. Iztapalapa T-Tach--Solidaridad 2 range residuals on Day 255 with bias removed.*

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# 4. CONCLUSIONS

This study has shown how well the CRDA range data can be calibrated with and without the assistance of dense Millstone radar tracking. When Millstone tracking is dense, as during a Telstar 401 encounter, the CRDA range data have been calibrated with residuals having a near zero mean and a scatter on the order of the measurement error of the data. Without dense tracking from Millstone, the biases can only be determined with higher uncertainty on the order of 20-40 m as shown in the examples. The dense Millstone data provides orbit control as a third geometric station with four measurement types, which also permits better maneuver modeling.

It has been seen that an orbit determined with dense Millstone data and other SSN data alone cannot calibrate the CRDA range data since diurnal residuals on the few hundred meter level show up indicating an error in the orbit based on these data. The CRDA data must be appropriately weighted and included in the orbit fit and, from the resultant residuals, biases determined. The biases that result are on the order of tens of meters.

The orbit arc lengths discussed here are generally two to four weeks long for bias determination and two weeks for orbit quality analysis. This choice of arc length is due in part to the fact that Millstone generally tracks for about a month to support Telstar 401 encounters. The suggested procedure would be to start with two-week fits, and build up through four week fits and longer if possible. Sliding four-week fits might be the most useful for maintaining an ongoing calibration.

From an operational standpoint, it is important to have the thrust information, particularly the time of the thrust. It has been found that all maneuvers need to be considered to determine the biases, even the small momentum adjustments. Since the procedures try to solve for the three maneuver components in the orbit fit as a general approach, the delta V's are not required. But they are used (if available) as a check. With dense Millstone data, the maneuver modeling works well enough to yield biases with uncertainty at the level of the measurement error. Without or with little Millstone data, just a more gross calibration can be maintained for the CRDA data as it is more difficult to fit through the maneuvers, and therefore residuals with scatter of 100 m or more result. Some success has been obtained with CRDA partner supplied delta V's, but accurate post-maneuver values would be required as well as further analysis and development with DYNAMO.

The orbit quality has been evaluated primarily with overlaps of orbit fits having a period of time in common. Experience has shown this to be a realistic indicator of orbit accuracy. The use of SBV data as an evaluator, as in Example 1, seems to confirm the overlap orbit quality. With dense Millstone tracking, which is available during Telstar 401 encounters, and the calibrated CRDA range data from two stations, orbit quality on the order of 100-200 m is realizable. Without dense Millstone data, the process of calibrating the CRDA data is not as good and using it in the orbit determination yields orbit quality or the order of 0.5 to 1 km. This is still a general improvement over what dense Millstone and other SSN data can routinely provide. The examples of using just the uncalibrated CRDA range data in orbit fits indicate that orbit quality on the order of 0.5 to 2 km can be achieved. If the calibration is known apriori and if the maneuvers can be accurately modeled or provided aprior significantly better results are obtained, as good as 100-200 m. These accuracy assessments are not a comment on how accurately the CRDA partners can compute orbits with their range data.

The Millstone only tracking determines the radial component of the orbit the best and the cross track component the worst. Millstone has very good range and range rate data, but errors in the azimuth and elevation errors that contribute to the cross track component. Addition of other range data or good quality angle data provides significant improvement in the cross track component.

There are still issues with regards to how distribution, frequency, and accuracy of the tracking data, as well as the number and type of tracking stations, can affect orbit accuracy. This needs to be investigated in a controlled manner as with Monte Carlo simulations, covariance analysis, as well as with the real data that are available. A study is now underway to understand some of these and other aspects of geosynchronous orbit accuracy.

# REFERENCES

1. R. I. Abbot, L. E. Thornton, and D.E. Whited, "Close Encounter Analyses of Telstar 401 with Satellites in the Geopotential Well 97-113 Degrees West Longitude," MIT Lincoln Laboratory, Lexington, Massachusetts, Project Report CESA-001 (May 1998).